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MINNESOTA GEOLOGICAL SURVEY

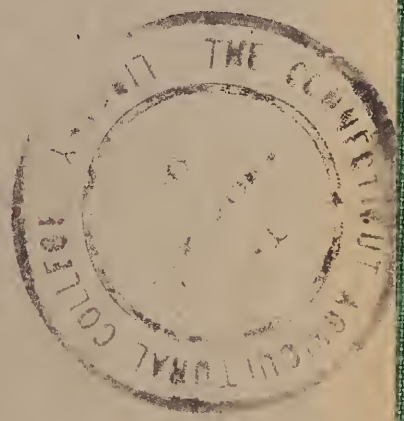
WILLIAM H. EMMONS, DIRECTOR

BULLETIN NO. 18

THE FOUNDRY SANDS OF MINNESOTA

BY

G. N. KNAPP



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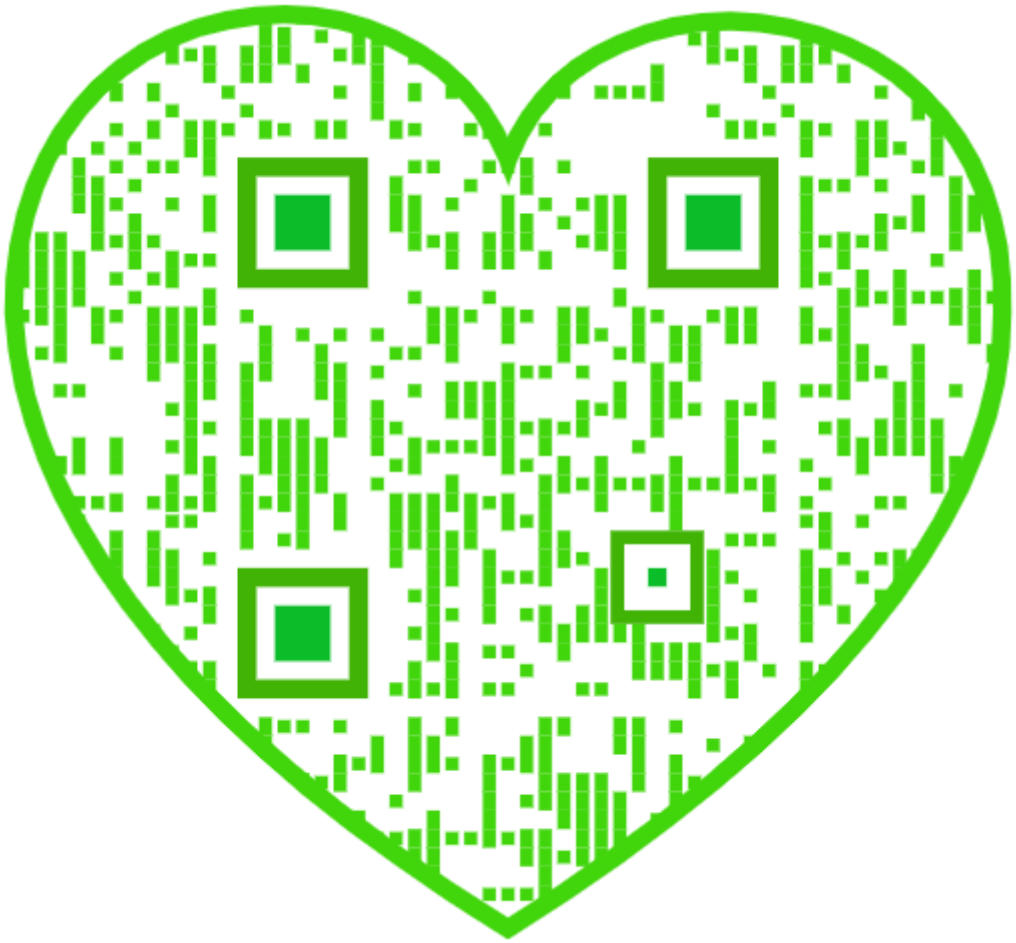

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PREFACE

This paper, on the sands of Minnesota, is a report of an investigation begun in 1918, at a time when there was a great demand for information about local molding sands, as a result of the traffic situation that made it difficult or impossible to obtain sands from sources that had previously supplied them. The inquiry, which was in charge of Mr. G. N. Knapp, showed that Minnesota contains an abundance of sands for founding nearly all products, equal to, or better than, the sands that had been imported. Part of the information embodied in the report was placed at the disposal of the metal founders as soon as it became available, either verbally or by means of mimeographed sheets.

The field work showed also that molding materials are more widely spread over the state than was supposed, and a fairly comprehensive reconnaissance was made of a considerable part of Minnesota. Materials gathered from widely separated sources were tested in the laboratory and some were tested by founders in their plants. Minnesota contains an abundance of foundry sands and all materials commonly used for making molds in foundries of iron, steel, brass, and aluminum, except possibly a highly plastic refractory clay.

An economic bulletin such as this is chiefly utilitarian. It should show the nature of materials used, the tests made to ascertain the value of the materials, and the distribution of the materials in the state. These subjects are taken up separately in this bulletin and the geologic and geographic distribution are discussed in some detail. The report does not contain a geologic map. To have included such a map would have resulted in duplication. A search for sands in the hard rock formations will be aided by the use, in conjunction with this bulletin, of the county geologic maps, published by N. H. Winchell and associates in the final report, Volumes I to V, *Geological and Natural History Survey of Minnesota.* The search for materials in the drift will be aided by the maps of surface formations and agricultural conditions, by F. Leverett and F. W. Sardeson, published by this survey, and included in *Bulletins* 12, 13, and 14, already issued. *Bulletin* 11, on the clays and shales of Minnesota, by Professor F. F. Grout and Dr. E. K. Soper,[1] will be found helpful in a search for clay binders, and *Bulletin* 663, of the United States Geological Survey, by Mr. Oliver Bowles, will show the sources of screenings from quarry operations, such as are used to a limited extent.

[1] Reissued as *Bulletin* 678, United States Geological Survey.

The economic bulletins of this survey are written principally for the use of the general public. We aim to state the results of investigations in terms that are non-technical. If we fail in this respect, and the results of the investigation are obscure, or if they do not contain the information desired, the officers of the survey are available for consultation. The survey charges no fee for such service.

WILLIAM H. EMMONS.

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THE FOUNDRY SANDS OF MINNESOTA

INTRODUCTION

When the Federal government in 1917, as a war measure, assumed control of the railroads of the nation, the founders of Minnesota were notified that the Railroad Administration would not continue to furnish cars for the shipment of sand from remote points, and were advised to find sand nearer home. The writer was detailed to investigate the problem of where foundry sands were to be obtained in Minnesota.

In the course of this work, begun in June, 1918, the southern part of the state from Taylors Falls to the Iowa line and west to Pipestone and Granite Falls was covered in a reconnaissance way by the writer; and Mr. V. T. Allen extended the work to foundries in the northern counties. Sands were found in various parts of the state similar in character and in some respects superior in quality to those which were then in use in the foundries and which had been imported from Missouri, Illinois, Wisconsin, Kentucky, and New York.

Circulars were issued by the Minnesota Survey in 1918 and 1919 on brass sand, quartz sand, foundry loams, and refractory clays of Minnesota, and distributed to the foundries desiring such information.

At the time this work was undertaken there were thirty-five foundries in Minneapolis and St. Paul actively engaged in casting the various metals. Some of them confined their operations exclusively to one line of work such as grey iron founding, steel founding, brass founding, or ornamental bronze founding; others covered a larger field, founding in grey iron, steel, semi-steel, brass, aluminum, and bronze.

Some of the foundries were content to use such sands and loams for molding as could be found in the immediate vicinity of their shops, and could be hauled by team or truck. Others having more exacting contracts calling for high finish to their castings resorted to artificial mixtures of sands and loams, or sands and clays, partly imported and partly obtained locally. Still others had imported all of their sands and clays from remote regions. One foundry doing ornamental bronze work imported a facing sand from France at a cost of $16 per barrel. The sand imported from New York chiefly for brass work, known as "Albany sand," cost f.o.b. Minneapolis about $15 per ton, while sand equally good for the purpose was found in Minnesota, costing 25 cents per ton in the pit, or $3 to $4 per ton at St. Paul.

Time did not permit gathering complete statistics of the amount of sand, loam, and clay used by the foundries of Minnesota, or the cost of the same, but from such statistics as were gathered it is roughly estimated

that the total amount used annually exceeded 100,000 tons; and as the price to the foundries ranged from $2 to $15 per ton, it is apparent that the cost is a very considerable sum.

The greatly increased demand within the past few years for a higher grade of casting, both as to the soundness of the casting and as to the finish or exterior surface, more especially in steel, brass, and malleable iron, has led to a great expansion of business in these lines. This demand was augmented by the contracts for war materials, and the rigid inspection and exacting conditions insisted on by the government.

Demand for a higher grade product has brought home to the founder the importance of the sand; the grade of the cast product depends largely on the quality of the sand forming the mold. The percentage of defective castings in some of the foundries visited was so large that the loss incident to scrapping them came near making a loss on the total operation. The defects in the castings, in a large majority of cases at least, were plainly due to the quality of the sand used in the mold or to improper handling of the sand. In only a small percentage of cases were the defective castings due to the metal, itself, or to the methods of handling the metal.

Most of the foundries were without laboratory facilities for testing their molding sands, except by screen analysis and chemical tests; accordingly when confronted by sand trouble that did not yield to empirical methods, they tried another sand usually a new one sought from the locality where some competitor making better castings was obtaining his sand.

In order to appreciate the problems connected with metal founding in Minnesota, most of the plants were visited and samples of the molding sands collected. These were studied in the laboratory. Later various geological formations within the state were studied in the field and samples collected from them. These were submitted to similar laboratory tests, and some of the most promising were supplied to foundries to be tested under actual working conditions.

The laboratory tests to which the samples of sand, loam, and clay collected in the foundry and in the field were subjected consisted in (a) a mechanical analysis, including a determination of the clay content by elutriation; (b) a test of the bonding power or tensile strength by breaking briquets made from the various materials; (c) determination of the porosity by comparing the weight of a given volume of sand with the same volume of non-porous rock; (d) a determination of the permeability by passing a measured volume of air under constant pressure through a core of sand of standard size; (e) a refractory test, which consisted in determining the point of incipient fusion of the materials in an electrical furnace, the temperature of which was controlled; and (f) a mineral analysis.

The following report in which the results of the investigation are recorded is divided as follows: the technology of the sand-consuming industries in brief; the geology of Minnesota with reference to the origin and distribution of sands, as well as some loams and clays; a description of the laboratory methods and the apparatus used in testing; and a tabulation and discussion of the results of the laboratory tests.

ACKNOWLEDGMENT

The writer is indebted to Professor W. H. Hunter and Professor R. A. Gortner for suggestions in problems of chemistry; to Professor H. A. Erikson for assistance in establishing tests for permeability and capillarity; to Professor F. F. Grout for aid in microscopic examination of silts, suggestions of laboratory methods, and criticism of the text; to Mr. V. T. Allen for mineral analyses of the sands and notes on the results and data from foundries in the northern part of the state; to Mrs. W. C. Knapp for mathematical computations and general editorial work; to Mr. H. K. Armstrong for assistance in the laboratory; to Dr. W. A. Schaper for suggestions as to arrangement of material; and to Professor W. H. Emmons for general direction of the work and for editing the report.

Special acknowledgment is due managers and superintendents of various foundries in Minneapolis and St. Paul for courtesies shown; to members of the technical force of these foundries for molding sand specifications, chemical analyses of sands and loams, and other valuable data; and to the skilled molders for the making of special cores and cylinders of molding sand and core sand for permeability tests.

FOUNDING

That certain metals were ductile, and by hammering could be fashioned into implements of war or the chase or into tokens and emblems, was discovered by primitive man in the early dawn of civilization, as evidenced by the relics found in the mounds and burial places of the ancient races.

That the native metals melt at moderate temperatures and that by mixing them in varying proportions, alloys could be made having properties superior for certain purposes to the metals themselves, was no doubt discovered also by early man. This achievement was a prominent one in the "Bronze Age."

The more important discovery that the ores of iron could be smelted and the metallic iron recovered in this manner, marked a still further advance in civilization and was possibly made in prehistoric times, at least such evidence as we have indicates that it was made more than six thousand years ago. The oldest iron implements come from Egypt and date

back more than five thousand years. The earliest recorded history has it that Tubal-Cain (B.C. 3875) was known as "master in every kind of bronze and iron work," indicating that the use of the metals had then reached an advanced stage.

Founding, or the art of casting metals, is such a simple matter, now that we are familiar with the procedure, that it seems strange that the process was not discovered and taken advantage of as soon as metallic iron was recovered by smelting the ores. One would suppose that the next step after having discovered the process of smelting would have been to bring the metals into a fluid state and pour it into molds or forms, in this manner casting implements of any form or shape desired.

It appears, however, that the first iron implements were made of wrought iron instead of cast iron; that is, instead of melting the iron and pouring it into molds, it was taken from the furnaces in the form of billets of white-hot metal and hammered into the form desired. So far as now known, wrought iron was used for one thousand years, and possibly two thousand years, before the art of casting the metal was discovered, or at least before cast iron was used industrially.

A discussion of the technique of molding and the methods of handling the melted metal has no place in the present report, except as it may aid those unfamiliar with the procedure better to appreciate the kind of material required for molding sand and for other foundry uses. A very brief outline of one of the simplest methods will suffice, and the reader, interested in further details, may find them in one of the numerous books on foundry practice.

If it is desired to make a sphere or ball of cast iron, or of other metal, the procedure is as follows: First a pattern is made, which is a counterpart of the ball to be cast. The pattern is commonly made of wood but may be made of other materials, such as clay, wax, etc. When made of wood the pattern is made in two parts, with dowel pins or other devices to hold them together and in alignment.

After the pattern is made the second step is to make a mold from this pattern. One half of the pattern is placed on the foundry floor, molding bench, or table, with the flat face downward. Around the pattern is placed a frame of either wood or iron of convenient size. This is simply a box without cover or top into which is packed molding sand until the frame is level full. The molding sand is simply damp sand having enough clay or other binding material in it to hold it together after it is packed or rammed in firmly. The frame, filled with molding sand in which the half pattern is embedded, is next picked up carefully and turned over, bringing the flat face of the pattern uppermost.

[1] Moldenke, R., Principles of iron founding, p. 2. McGraw-Hill Book Co., New York, 1917.

The other half of the pattern is then placed in position on the half buried in the sand. A second frame is placed upon the first; the surface of the sand in the first is sprinkled with dry sand or dust to make a parting, so that the molding sand to be rammed in will not stick to the sand in the first frame. The second frame is then rammed full of molding sand level with the top. The upper frame, filled with sand, is then lifted off, and the halves of the pattern removed from the sand, leaving an impression, or "mold," in the sand the exact size and shape of the halves of the pattern. The two frames are again placed one upon the other in exact alignment so that the spherical cavity, or mold, in the center of the sand mass will be a sphere. The two frames are then locked together and weights are placed upon the upper surface of the sand.

In ramming in the sand a small hole, called a "riser," is left from the face of the pattern to the surface of the sand in one of the frames. This serves as a passage through which the melted iron or other metal may be poured into the mold.

The frames above described constitute a "flask." A flask is simply a rigid container made of two or more parts and serves to hold the rammed sand in position so that it may be lifted, carried around, or turned over. It also serves to reinforce the sand against the pressure of the metal and against the steam and gases generated in the sand when the hot melted metal is poured in. Flasks vary from simple one-piece boxes to complicated many-piece devices and in weight from a fraction of a pound to many tons.

After the different parts of the flask are in position so that the mold is complete the melted metal is poured into the mold and allowed to stand for a period varying with the size of the casting from a few minutes to an hour or more. As soon as the metal is set, and usually while it is still red hot, the flask is lifted apart and the metal casting is shaken out on the foundry floor where it lies in the loose sand until cooled sufficiently to handle.

As soon as the molding sand has cooled to room temperature, it is used again, the process being repeated as long as the sand has binder enough to stand up in the mold. Clay or new loam is added from time to time to replenish the bonding material which is destroyed by the heat.

Some cast articles are so small or have so many reëntrant angles, that it is not feasible to make two-piece patterns. In such cases a pattern is made of wax, which is a counterpart of the article to be cast. This wax pattern is embedded in the molding sand in a metal flask. The molding sand is then heated to a temperature sufficient to burn up or vaporize the wax which disappears leaving a mold in the interior of the sand mass, which in turn is filled by pouring the metal into the mold. This process is commonly employed in casting ornamental tablets and figures in bronze,

aluminum, etc., and is extensively used in modern dentistry in casting gold fillings, and other restorations for teeth. In fact the adaptation of casting in metals, and the diversity of patterns, materials, and processes are almost unlimited.

NATURE OF SANDS AND LOAMS FOR FOUNDRY MOLDING

A great variety of earthy materials is used in the modern foundry under the general names of loam, clay, and sand. The loams used include material ranging from very fine silts to coarse sandy materials with a greater or less amount of gravel, and a clay content ranging from 2 to 10 per cent. The sands used range in mineral content from pure quartz sand to material bordering on loams, in which a variety of materials is present, with more or less clay; and in size of grain they range from material the bulk of which would just pass the 20-mesh screen, to material the bulk of which would pass the 100-mesh screen. Foundry clays range in physical constitution from the purest clay obtainable to ordinary loams, and in refractoriness from the highest testing fire clay to the ordinary glacial clays with a high content of lime and other impurities causing them to fuse readily.

The sands and loams used in the foundry for molding purposes may be divided roughly into classes, according to the function which they perform, as follows: (1) sands used for making the cavities or holes in the metal castings; (2) sands or loams used to make the mold or container which gives the casting its exterior form. The former are called core sands, and the latter are called molding sands or loams.

CORE SAND

For core work a clean sand free from clay is preferred. To this clean sand is added some organic bonding material such as glue, resin, linseed oil, molasses, etc. The heat of the metal will destroy the bond, leaving the core sand incoherent so that it may be readily removed from the cavities of the casting. Greater permeability is obtained in this manner than is possible where loamy materials are used.

The texture and quality of sand used for core work vary greatly and depend on the nature of the founding. If the cores are surrounded by large masses of metal and the temperature of the melt is high, a greater degree of permeability in the cores is required than if the metal mass is small and the temperature low. Where a high degree of permeability is required, a sand of coarse texture in which little or no silty material is present is generally used. If the temperature of the melt is low or the mass of the casting is small, finer sands give satisfactory results for core work.

Quartz sand entirely free from clay is preferred for core work, but it is seldom found in nature in commercial amounts, and sands with one and two per cent of clay are in common use. Glacial sands having a varied mineral content are also used.

MOLDING SAND

As generally defined a molding sand is a siliceous sand having a clay content just sufficient to bind the sand grains together, but not enough to fill the voids between the sand grains; so that when moistened slightly the mass may be molded into any form desired, retaining this form when dry and being sufficiently open or permeable so that air may be blown through it.

The chief requisites of molding sand, then, are permeability and tensile strength or ability to resist rupture. Molding sand must be permeable because when the hot liquid metal is poured into the sand mold considerable volumes of steam and gas are generated in the sand. These must have the opportunity for ready escape, otherwise the mold will be blown to pieces by accumulated gas pressure before the metal has opportunity to set or cool. Molding sand must have sufficient bond so that the walls of the mold will stand up against the pressure of the liquid metal, which in large castings is considerable, and it must withstand the wash of the liquid metal as it is poured into the mold.

Permeability and tensile strength requirements differ, consequently there is no exact standard to which all must conform. In certain classes of founding large volumes of gas are generated in the sand and a high degree of permeability is required, whereas in other classes of work but small amounts are generated and much less permeability is satisfactory. In the same manner the tensile strength or bonding power required of molding sand varies with the character of the founding. Accordingly a certain sand may be entirely satisfactory for one class of molding and unsuited for another.

Other requisites of molding sand are certain textures and refractoriness, but these also are measured by relative rather than absolute standards and depend on the class of founding done. For example, if the temperature of the melt is high, say 3000° F., the molding sand can have but a small content of lime, alkalies, iron oxide, and other fluxing impurities; otherwise the sand in contact with the metal will be fused or melted and will stick to the casting. For such work a refractory molding sand is essential. If, on the other hand, the temperature of the melt is less than 1000° F., as in most brass work, there is little likelihood that the sand will be fused, and refractoriness as a property of such molding sand is for practical purposes negligible.

The texture required of molding sand also varies with the class of founding. Some metals when melted are much more fluid than others and the fluidity of the same metal increases as the temperature is raised above the melting point. If the molding sand is very open and porous and the melt is of a high degree of fluidity, the liquid metal will penetrate the sand or "search the sand," as the molders say. If the sand is exceptionally coarse in texture the face of the mold will be pitted and the surface of the casting made will be rough. For certain types of metal and for certain requirements of finished surface, molding sands of finer texture are required.

Since a molding sand consists of a mixture of sand and clay it may be made artificially by mixing clean sand with the required amount of clay to give the desired bond. In fact, some foundries prefer molding sand made in this manner. But in nature, sands and clays occur ready mixed in every conceivable proportion and most of the molding sands and molding loams are these natural mixtures.

There are no simple tests and no infallible rules or formulae by which the inexperienced may judge whether or not a loam or sand may be suitable for molding purposes but the skilled molder can usually judge the suitability of a given sand or loam for molding purposes by simply kneading it in his hands and by blowing air through it after molding it. The only satisfactory way for the layman to determine the probable value of such material for foundry use is to submit samples to experienced molders or foundrymen, or have the same subjected to laboratory tests.

"DOCTORING" MOLDING SANDS

It is well known that sands and loams as they occur in nature are rarely uniform in character. In any sand bank or pit the material usually varies in character from the surface downward, as well as laterally; so that even if a sample of material is found having the right constitution for molding, there is no assurance that any considerable deposit will be found of exactly the same character. In actual foundry practice variations in the sand or loam are anticipated and the material is brought to the desired consistency by adding the constituents that are lacking. If the loam is too heavy and lacks permeability, clean sand is added; if it it too sandy and lacks bonding power, clay or heavier loam is mixed with it. Coal screenings or ground coal, called "sea coal," is sometimes added. Sawdust, chopped straw, and other similar organic materials are commonly used to give the desired texture and increase the permeability. Organic materials, such as glue, molasses, flour, stale beer, resin, linseed oil, glucose, etc., are frequently employed to increase the bond. This practice of modifying the consistency by adding certain constituents is called "doctoring" the sand.

After the sand has been used in the mold one or more times, the bond is destroyed to a greater or less extent by the heat and the burned products accumulate in the sand as fine silty material, decreasing the permeability and changing the texture. Before being used again, the sand is doctored by adding such materials as will bring it back to the desired consistency. Thus the molding sand, which is continually deteriorating with repeated use, is restored to the proper consistency as to texture, bond, and permeability by repeated doctoring which may consist in adding a single constituent or several constituents. In the ordinary foundry doctoring the sand is a part of the daily or hourly routine and taxes the skill and judgment of the molder to the limit. The grade of casting produced in a foundry, so far as soundness and exterior finish are concerned, depends largely upon doctoring to keep the sand to a uniform consistency.

OUTLINE OF GEOLOGY OF MINNESOTA

The materials used in the foundries include a rather wide range of products of rock weathering, i.e., different types of sands, loams, and clays that have been redistributed and redeposited by wind, glaciers, rivers, lakes, and the sea, and as now found are frequently far from their original sources. In view of this it was believed that the origin of this foundry material might be better understood and its variation in character better appreciated if a description of the material itself was prefaced by a brief account of the general geological relations of the state, the rock formations present, and the sequence of events leading up to the present disposition of the surface materials. In the following geological description the writer has borrowed freely from previous published reports on Minnesota geology.

All of Minnsota except the extreme southeast corner is a broad glaciated plain differing only in minor details from the adjacent regions to the west, north, and east. The minor topographic features of this great plain are the result of glaciation and stream erosion that has taken place in postglacial time. They consist of:

(a) Numerous belts of low knolls or gravelly hills, known as terminal moraines in which are innumerable small undrained basins, kettle holes, or ponds. These moraines represent the material that accumulated at the margin of the glacier in various stages of its advance and retreat and consist of a mixture of all types of material that was picked up from the local rock formations over which it passed. This morainic material, known as "glacial till," while exceedingly heterogeneous in mineral content and physical character, at many places contains material that can be used in foundry work, as the detailed description shows.

(b) Broad, gently sloping plains or prairies of more or less well-assorted gravels and sand, known as outwash, usually fronting the terminal moraines, or otherwise definitely related to them, and representing the material carried out from the ice margin by glacial waters. These gravel plains are usually mantled by loam a few feet in depth, which is serviceable in foundry work, but the sands beneath rarely are.

(c) Broad, comparatively flat tracts in which occur occasional low hills or knolls and many shallow ponds or lakes. These tracts are underlain by glacial till, known as ground moraine. The surface mantle of loam so persistent throughout the state is usually, though not always, present in these areas but is not ordinarily so well suited to foundry purposes as the loams otherwise disposed.

(d) Long, gently sloping plains, usually narrow, that follow the present valleys or the lines of drainage in glacial time. They are underlain by gravels and sands more or less assorted and stratified. Some of these are similar in origin to the outwash plains and frequently are only continuations of such plains, whereas others are postglacial in age and represent the material redistributed by streams since glacial time. They are sometimes called valley trains. The usual mantle of surface loam is common in these areas and often affords good foundry loam.

(e) Narrow plains of gravel and sand more or less well assorted that skirt the border of extinct lakes of glacial age. They seldom carry material of value in foundry work.

The glacial material varies in thickness from 0 to 500 feet. If it were spread uniformly over the area where now found, it would be less than 100 feet thick. It is in reality only a veneer that mantles the topography of pre-glacial time and serves merely to mask the minor details of that ancient surface in some places and to conceal them entirely in others. In a major way Minnesota was a broad low plain in pre-glacial time, on which were well-established lines of drainage with broad shallow valleys and the usual minor topographic features characteristic of stream erosion. The bed rock of the old formations appears at the surface at innumerable places in the glaciated area where the glacial drift was originally thin or absent and where subsequent stream erosion has uncovered it.

At present Minnesota stands somewhat higher than in pre-glacial time. The southern portion of the state, considered broadly, is a low plateau with one elevated area in the southwest corner of the state, known as the Coteau des Prairie, rising to an altitude of 1,900 feet, or about 500 feet above the general level, and a second domed or elevated area in the southeast corner, rising to 1,400 feet above sea level, which is about 400 feet above the general level.

Northern Minnesota possesses a more varied topography. The northwestern part is as flat as a floor, except for a series of low ridges, being the site of the ancient Lake Agassiz. The extreme northeast part of the state is more rugged with several low "ranges" rising to altitudes of 1,800 to 2,000 feet.

The southeast corner of the state, representing about one sixteenth of its total area, is altogether different from the rest of the state in topographic appearance. In a portion of this area, in Houston and Winona counties, glacial drift is absent and probably was never present. It is a part of the so-called "driftless area" of the upper Mississippi Valley. Here natural lakes and ponds so abundant in the rest of the state are entirely absent and the surface everywhere slopes toward the streams that drain it.

Bordering the Mississippi River in this area the tributary streams coming from the west have cut valleys 200 to 500 feet deep, which in places are gorgelike and in other places are flat-bottomed, walled in by cliffs of massive limestones and sandstones of the old Paleozoic formations. Between the valleys the upland areas are commonly rather flat or very gently sloping, plateau-like in aspect, and are remnants of an old plain of stream degradation developed in pre-glacial time when the land stood much lower than now.

The uplands in this area are more or less completely covered by a siltlike loam called loess, to be described later, 0 to 40 feet in depth, which mantles the high points and reaches down the valley slopes even to the streams in places. The old rocks native to the region are largely buried by this loess but in the steeper slopes they protrude and exposures are seen in abundance.

The rocks of Minnesota[2] range in age from the most ancient known as the Archean to the youngest which are now in the process of deposition along the present streams and in the lakes and are known as recent. The accompanying tabulation shows the principal formations present in the state arranged in their proper sequence with the oldest at the bottom. It will be observed that there are two breaks in Minnesota's stratigraphic

[2] Winchell, N. H., Geology of Minnesota: Final Report Geol. and Nat. Hist. Survey of Minnesota, Vols. 1 to 5, 1882-1900.

Leverett, F., Surface formations and agricultural conditions of northwestern Minnesota: Minnesota Geol. Survey Bull. 12, pp. 1-75, 1915.

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Bowles, O., Structural and ornamental stones of Minnesota: U.S. Geol. Survey Bull. 663, pp. 1-225, 1918.

TABLE I. GEOLOGIC COLUMN OF MINNESOTA

Era	System and Series		Formation	Approximate Thickness	Character of Strata	Value for Foundry Use
CENOZOIC	Recent		Recent	0 to 300	Sands, silts, clays, muds	Little or none Valuable
	Pleistocene		Glacial	0 to 600	Loess, gravel, sand, loams, clays	Loams valuable, sands less so
MESOZOIC	Cretaceous		Benton shale Dakota formation	0 to 550	Clays and shales Sands, clays	Clays valuable, sands less so
PALEOZOIC	Devonian			100	Sandstones and limestones	No value
	Ordovician		Maquoketa	100	Shale and limestones	No value
			Galena Decorah Platteville	230	Limestone Shale Limestone	No value
			St. Peter	80-200	Sandstone	Valuable quartz sand
			Shakopee	100	Dolomite	Small value
			Oneota	75-200	Dolomite	Small value
	Cambrian		Jordan	75-200	Sandstone	Most valuable quartz sand in state
			St. Lawrence	100-200	Dolomite and shale	No value
			Franconia	50-100	Sandstone	Little or no value
			Dresbach	300-450	Sandstone, shale, and limestone	Little or no value
PROTEROZOIC	Algonkian		Red Clastic series in southern Minnesota, sandstone in northern Minnesota	2,250 maximum	Sandstones and shales	Kettle River sandstone valuable for quartz sand Other sandstones also
	Keweenawan		Conglomerate and sandstone	500	Conglomerate and sandstone	Little or no value
			Eruptives	Unknown	Igneous rocks	No value
	ALGONKIAN / HURONIAN	Upper Huronian (Animikie Group)	Intrusives	Unknown	Acid and basic igneous rocks	No value
			Virginia and other slates	3,000	Slates	No value
			Biwabik and Gunflint	800	Taconite, iron ore, chert	No value
			Pokegama	200	Quartzite, Sioux quartzite	Valuable for quartz sand
		Lower Middle Huronian	Giant Range	Unknown	Granite, dolomite porphyries	No value
			Graywacke	5,000	Slate, graywacke, conglomerate	No value
	ARCHEAN		Residual clay		Residual clay	Possibly valuable
		Laurentian	Igneous rocks	Unknown	Granites, schists, porphyries	No value
		Keewatin	Soudan	Unknown	Banded cherts and jaspers, iron ore	No value
			Ely and other formations	Unknown	Greenstone, schists, porphyries	No value

record. One occurs between the Ordovician and Devonian, the Silurian rocks being absent; and a second occurs following the Devonian, the Carboniferous, Permian, Jurassic, and Triassic rocks being absent. The Cretaceous is found lying directly on the Devonian and older formations.

Archean period.—The rocks of the Archean system in Minnesota are divided into two groups, i.e., the Keewatin group at the base and the Laurentian group above. The Keewatin epoch was one of vulcanism and the rocks of the Keewatin group consist largely of lava flows that are for the most part basic. The land evidently stood low for water-laid sediments were deposited alternating with the lava flows.

The entire series of beds was subsequently complexly folded and profoundly metamorphosed converting the basalts into green schists now seen in outcrop in much of the northern part of the state.

The Laurentian epoch resembled the Keewatin in that igneous activity was dominant, but the igneous material was intruded instead of being extruded as lava flows.

The rocks of the Archean period in general are of little value for foundry purposes unless it shall be found that some of the more refractory schists may be serviceable for furnace lining.

Algonkian period.—The rocks of the Algonkian period are divided into three groups which from the base upward are known as the Lower-Middle Huronian, the Upper Huronian, and the Keweenawan.

As compared with the Archean the Algonkian period was one of sedimentation, but pronounced igneous activity occurred at intervals during which times igneous material both basic and acid and of several types was intruded in the stratigraphic series.

At the close of the Middle Huronian epoch the region was lifted above sea level and more or less erosion occurred, resulting in an unconformity between the Middle and the Upper Huronian groups.

The water-laid sediments of the Algonkian period consisted of gravels, sands, and muds which as the result of complex alterations by both chemical and dynamic metamorphism were changed to conglomerates, sandstones, quartzites, shales, and slates. Some of these formations, as will appear from the more detailed description, yield foundry sand, particularly the quartzite at New Ulm and the Sioux quartzite (pp. 18 and 19).

The Red Clastic series.—Above the Keweenawan beds there appears a group of beds known as the Red Clastic series, about 2,250 feet in maximum thickness, consisting of shales and sandstones, which are provisionally referred to the Algonkian. Locally this group carries sandstones of exceptionally high quartz content such as the Kettle River and Hinckley sandstone and certain sandstones in vicinity of Duluth which furnish good sand for refractory purposes both for foundry and for steel furnace use.

Cambrian period.—At the close of the Algonkian period all of Minnesota stood above sea level and there was a prolonged period of subaerial erosion and decay of the old crystalline rocks. The region remained in this relation through the greater part of the Cambrian period and not until late Cambrian time did it subside, permitting the sea to encroach from the south and west, resulting in the deposition of sand, sandy muds, and sandy limestones over the greater part of southern Minnesota. The northern part of the state probably remained above sea level throughout Cambrian time and continued to suffer erosion instead of deposition.

The Cambrian group of beds in Minnesota consists of four formations which from the bottom upward are known as the Dresbach, Franconia, St. Lawrence, and Jordan. The Cambrian sea was shallow throughout the period and the long period of subaerial decay preceding the Cambrian submergence had prepared a vast amount of soft and loose material for redistribution by the shallow Cambrian waters. This is evidenced by the incomplete sorting of the material in the Dresbach and Franconia formations, and the rapid alternation of thin beds of fine sand and sandy mud in these formations.

In the last epoch of the Cambrian period, i.e., the Jordan, conditions were somewhat different, either as to supply of material or as to depth of the sea, with the result that a quartz sand of exceptional purity was deposited over a wide area in the southern part of the state.

There was little if any orographic movement during the Cambrian period and there has been but little since, so that the Cambrian beds have hardly been disturbed and very slightly altered in most places. The Cambrian beds lie in nearly horizontal position much as they were deposited and in many localities are so slightly cemented that they may be mined with steam shovel or by hand without the aid of blasting.

The Cambrian formations carry many beds of sand that locally are sufficiently well assorted and of sufficiently clean quartz to be valuable for foundry purposes; but the uppermost member, i.e., the Jordan, so far exceeds the other formations in the quality and abundance of the sand that the other Cambrian formations are hardly worth special consideration.

Ordovician period.—There was apparently no elevation of the region at the end of Cambrian time—on the contrary, probable further subsidence—and deposition continued without interruption into the Ordovician period. The first deposits were calcareous muds now recognized as the Oneota and Shakopee dolomites through which appear numerous thin beds and lenses of quartz sand often remarkably clean and not unlike the Jordan.

After the deposition of these calcareous muds of the Shakopee, there was a slight elevation of the region, shallow water conditions prevailed over a remarkably wide area and a quartz sand, known as the St. Peter, was spread over all of southern Minnesota and adjacent parts of Wisconsin and Iowa, reaching far southward into Illinois, Missouri, and beyond. For uniformity of material and areal extent, this is one of the most remarkable formations in the United States. About the continental border to the northward the slight elevation at the beginning of St. Peter time probably brought the Jordan formation above sea level. The Jordan here was eroded and redistributed, thus contributing in part to the St. Peter deposition; but the original crystalline rocks to the northward, deeply decomposed, were probably the chief source of this great supply of quartz sand.

Following the St. Peter epoch there was a slight subsidence of the region and the recurrence of conditions favorable to the alternate deposition of limestones, muds, and clays which are now recognized as the Platteville limestone, the Decorah shale, the Galena limestone, and the Maquoketa shale. The shale formations in this series afford much clay which is being used extensively in the manufacture of brick, terra cotta, tile, etc., but because of the large content of fluxing impurities these clays are of little interest in foundry work. The Ordovician series of beds is of chief interest to the foundry industry for the supply of quartz sand afforded by the St. Peter formation described in more detail in the following pages.

Devonian period.—With the close of the Ordovician period the region was again elevated and remained above sea level throughout the Silurian period, after which subsidence again occurred sufficient to allow the sea to encroach upon the southern part of the state, causing the deposit of the Devonian limestone 50 to 100 feet thick, together with some shale.

Cretaceous period.—Following the Devonian deposition the region was again elevated and remained above sea level for a very long time, i.e., throughout the Carboniferous, Permian, Jurassic, and Triassic periods.

The elevation was apparently slight and not much erosion was accomplished. The relations, however, were such as to permit the decomposition of the old crystalline rocks to considerable depths; the feldspars were changed to kaolin or clay in which the quartz and other resistant mineral remained embedded, the sedimentary rocks such as sandstones and quartzites disintegrated into sand, and the limestones were leached, leaving a clay residuary. Thus there accumulated a great amount of loose or soft material ready for redistribution when later the region again subsided and the Cretaceous sea encroached upon the land.

This sea encroached upon Minnesota from the south and west re-working the accumulated products of rock, weathering and redistributing them, depositing sands and clays with some limestone upon the upturned edges of the older eroded formations. It is thought the Cretaceous deposition reached as far north and east as the Mesaba Range.

After the Cretaceous period the region was again elevated and stream erosion carried away much of the material that had been deposited but considerable areas in the southwestern part of the state remained, and detached areas or erosion remnants of greater or less extent are found in other parts of the state. These afford valuable supplies of semi-refractory clay and some sand of importance in the foundry industry, as appears in the more detailed description of these deposits which follows.

Pleistocene.[3]—Just before the Pleistocene epoch began the larger features of the topography of Minnesota were much the same as now. The advance of the ice, however, scoured out some valleys, filled in others, and deposited drift over large areas, entirely changing the details of topography and drainage. The retreat of the ice, by melting, formed marginal lakes and swollen, heavily silted streams, with further deposition and modification of topography.

The Pleistocene deposits show a peculiarly complex history, recording not only recurring stages of glaciation separated by long stages of deglaciation but also a complexity of ice movement within a single glacial stage. In the latest stage (known as the Wisconsin stage) there was one movement into Minnesota from the northwest, another from the north, and a third from the northeast; and possibly there was similar complexity in earlier stages. These movements were not synchronous in their advance, culmination, and waning, but each had its time of waxing and waning.

The oldest glacial deposit, known as the pre-Kansan or Nebraskan drift, is almost completely buried beneath later deposits. The attenuated edge of this drift may be exposed outside the Kansan drift in the southeastern counties.

Clayey and silty deposits found in a few places under the Kansan drift may represent accumulation in the Aftonian interglacial stage. They are, however, thin and of small extent.

The Kansan drift is extensively exposed in the southeastern part of Minnesota and in Pipestone and Rock counties in the southwestern part. It is generally of clayey texture, but as a rule carries limestone pebbles. It contains local pockets or lenses of marly pebbleless clay.

Weathering has somewhat modified the character of the upper part of the Kansan drift and wind has coated much of the surface in the

[3] Leverett, F., Clays and shales of Minnesota: U.S. Geol. Survey, Bull. 678, p. 77, 1919.

southwest corner of the state and some of it in the southeast part with several feet of loess, a pebbleless deposit of fine dust. Recent wash has moved some loess and some drift down sloping hillsides and so mixed them that the precise mode of origin of some particular clay banks may not be easily determined.

The Wisconsin gray drift, which was deposited by an ice sheet moving from Manitoba across western and southern Minnesota, is largely of clayey texture, but, like the Kansan drift, contains many pebbles, a large part of which are limestone. In places some lenses and pockets of pebbleless clayey material are included in the stony clay.

The Wisconsin drift that was deposited by glaciers invading eastern and central Minnesota from the north and northeast is in large part stony and sandy and contains very few bodies of silt or clay.

Locally streams of water from the melting ice spread fine sandy clays over what are called outwash plains.

The lake silts laid down in bodies of water in the western part of the Lake Superior basin and in the Red River basin are in places very thick, as at Wrenshall, but generally there is only a thin deposit of lacustrine sediment in the deep pools of these old lake beds and in certain localities there is only sand.

On the borders of the Lake Superior basin red boulder clay was deposited in large quantities; it is now dissected by steep gorges.

In addition to the great glacial lakes of the Lake Superior and Red River basins, there were numerous small lakes or ponded areas along the border of the ice, in which silt was deposited. Such an area lies north of Princeton at the large plants of Brickton and similar areas lie farther east along the northern border of a district which was occupied by a lobe of ice that extended northeastward from the Mississippi to the St. Croix Valley, above the Twin Cities. These clays were, in places, overridden by the later advances of the ice.

Recent.—Since the final disappearance of the Pleistocene glaciers there have been only slight modifications of the surface and very little accumulation of material or removal by erosion. A few lakes and swamps have been drained, and a few have been filled. The large river channels have been covered with silt.

GEOLOGICAL FORMATIONS YIELDING FOUNDRY SANDS, LOAMS, AND CLAYS

The Sioux quartzite formation.—The oldest geological formation of importance to the sand industry is the Sioux quartzite which belongs to the Upper Huronian group, in the Huronian system.

This quartzite is exposed at numerous places in the state but because of its hardness it is expensive to quarry and is of little service in foundry work except when crushed. This quartzite is extensively quarried at Courtland on the Minnesota River; in Nicollet County, sometimes called the New Ulm quartzite; also at Pipestone, Jasper, and Luverne in the southwest corner of the state, and at Sioux Falls, South Dakota, where it is known as the Sioux quartzite.

By reason of its extreme hardness, density, and toughness, this quartzite withstands attrition and abrasion to a remarkable degree and is much in demand as "pebbles" for ball mills. The quarries at Jasper supply the trade. The quartzite is cut into rectangular blocks about 3x3x4 inches, which are rounded to pebble shape by tumbling in revolving cylinders, and are shipped for use in ball mills.

The defective blocks and rubble of the quarry are crushed for concrete aggregate and for road material, and in the process of crushing more or less fine material results, which is screened out and sold as sand, the general texture of which is shown in the mechanical analyses Nos. 200, 205, and 207, Table XIV. This sand, screened to the proper size, should be very effective as a blast sand for foundry use and should be valuable also for refractory purposes as the following determination of the mineral composition shows[4]:

Quartz, (SiO_2), 96.3 %; Orthoclase ($KAl\ Si_3O_8$), 1.4 %
Zircon, ($Zr\ SiO_4$), .1 %; Hematite (Fe_2O_3), 2.2 %

It probably would not be feasible to crush the Sioux or New Ulm quartzite for fine screenings or sand, but where such screenings may be obtained as a by-product at a nominal cost they are worthy of consideration for foundry use both as refractory sand for furnace linings and as blast sand. It should be noted that it is quartzite of this type that is elsewhere crushed and used in the manufacture of "ganister" brick for furnace lining, a small amount of lime or other fluxing material being used to insure incipient fusion to bind the material when burned.

The Kettle River formation.—In the vicinity of Hinckley, Pine County, midway between St. Paul and Duluth there is a quartzitic sandstone known as the Kettle River or the Hinckley sandstone which underlies a considerable area. It is concealed by a thin mantle only of glacial drift and the streams of the region have uncovered it at numerous points. Kettle River has cut a narrow canyon through it 50 to 100 feet deep for a distance of several miles.

At the town of Sandstone, on Kettle River, extensive quarries have been opened in the formation, for the rock is a high-class building stone, and until a few years ago when concrete so largely replaced stone for structural purposes, was much in demand and has been used in numerous

[4] Bowles, O., *op. cit.*, p. 202.

buildings in Minnesota, Iowa, Illinois, and South Dakota. Laboratory tests show that this Kettle River sandstone used as aggregate makes a superior concrete and there is at present a growing demand for it for this purpose so that the output of the quarries at present is largely crushed rock.

In density this rock is about midway between the Sioux quartzite and ordinary sandstone. The cementing material is principally silica and the quartz grains of the original rock have to a large degree been enlarged by secondary quartz showing crystal faces. The rock, however, is still granular and upon crushing breaks along the faces of the grains instead of through the grains themselves. The screenings that result from crushing are more nearly true sand than are those from the Sioux quartzite, and a greater volume is obtained. These screenings are sold as sand and have been used for refractory purposes in the foundries of Minneapolis and St. Paul and in the steel furnaces of Duluth with satisfactory results. The subangular shape of the grains and their roughened surfaces offer good attachment for the bonding material which is an advantage for certain purposes. The comparative mesh of the sand, as shown by 185B, Table X, is 58, over 35 per cent being coarser than 60-mesh sand.

Chemical analyses of the Kettle River sandstone show the following composition:

	No. 1	No. 2
Silica, SiO_2	97.10	98.69
Alumina, Al_2O_3	2.20	1.06
Lime, CaO	.60	.42
Magnesia, MgO	.10	.01
Potash, K_2O		trace
Soda, Na_2O		.17
	100.00	100.35

No. 1. Analysis by United States arsenal, Watertown, Mass.
No. 2. Winchell, N. H. Geology of Minnesota, Vol. 1, p. 202. 1884.

The Jordan formation.—The Jordan formation which is the uppermost member of the Cambrian group underlies all of southeastern Minnesota, but being overlain by several younger formations, it is deeply buried in the greater part of the area and is known to be present only from the records of deep wells. Natural exposures of the formation are seen, however, along the northwest border of the area. There are exposures along the valley of the Minnesota River and along the Mississippi below Red Wing where such tributaries of the Mississippi as Zumbro and Rock rivers have cut into the Cambrian beds.

The only pits where the Jordan was being mined for sand on a commercial scale were found in the valley of Minnesota River in the vicinity of Ottawa and Kasota, Le Sueur County. The pits in these localities were one-half to one mile from the railroad stations and all are between the railroad and the river. Numerous other exposures where good sand might be obtained from the Jordan were seen between Ottawa and Merriam Junction, thirty miles to the northeast, but no pits had been opened. There was little inducement to open new pits because the pits at Ottawa and Kasota are almost ideally located. They are close to the railroad, have excellent drainage, and the banks of sand are 10 to 20 feet deep. The sand is so slightly coherent that a steam shovel might be operated without blasting. Sand could be produced there in practically unlimited quantities at a nominal cost per ton.

The southeastern part of the state in Wabasha, Winona, and Houston counties was not studied in sufficient detail to determine to what extent the Jordan is being used as a source of sand in this part of the state, or its availability.

The samples of Jordan sand, collected in Fillmore County at Preston and in Wabasha County at Mazeppa, were so similar in texture and mineral content to those collected from the Jordan sandstone in Le Sueur County that it was difficult to distinguish between them. These samples, together with field observations generally, serve to show that the Jordan is remarkably uniform in character over wide areas. Cursory examination showed it difficult to find anything but quartz in most of the samples. There can be little doubt that the Jordan furnishes sand as nearly pure quartz as any sand in the state. The formation which is 75 to 200 feet thick is not entirely uniform in character or in texture, but in all localities where good exposures of the formation were seen, beds 10 to 20 feet in thickness were found in which the sand was essentially pure quartz, with a texture such as shown in samples 8, 19, 170 etc., Table X.

The sand of the Jordan formation, in its coarser phases at least, which are preferred for foundry work, consists of quartz grains which in the larger sizes, i.e., the 20 and 40 mesh, are exceptionally well rounded; in fact occasional grains are found that are almost perfect spheres and even in the smaller sizes, i.e., 60 and 80 mesh, the grains are less angular than in average quartz sand.

Standard sand, known to the engineering testing laboratories throughout the country as Ottawa sand, comes from Ottawa, Illinois, and consists of essentially pure quartz sand sized to 20 mesh. Sand of this size screened from the Jordan sand from Ottawa, Minnesota, or from Merriam Junction can not be distinguished from the standard sand of Ottawa, Illinois.

Other sand formations occur in the Cambrian group in Minnesota in the Franconia and Dresbach formations, but in uniformity of texture, mineral content, and in availability they do not compare favorably with the Jordan sand.

The St. Peter formation.—The St. Peter formation appears in the geologic section about 200 feet above the Jordan formation and belongs to the next higher group or system, the Ordovician.

The St. Peter like the Jordan consists essentially of quartz sand. It is even more widespread than the Jordan, extending eastward and southward far beyond the boundries of Minnesota. It is rarely cemented sufficiently to be of value as building stone and is on the whole finer than the Jordan. Certain horizons in the St. Peter formation locally are as coarse as the Jordan, but rarely are such horizons thick enough to warrant separating them from the finer beds above and below.

In fresh exposures the St. Peter sand is usually very white and it has the appearance of exceptional purity but a bank sample of the material usually contains 1 to 2 per cent clay which is more than the Jordan carries. It also contains more silt than the Jordan.

For ordinary core work in foundries the St. Peter is very satisfactory, and since it constitutes the bed rock underlying the greater part of Minneapolis and St. Paul an ample supply of this sand is available in these cities. The St. Peter sand upon weathering takes on a yellow color due to iron staining and in this condition is sometimes preferred to the fresh white sand in foundry work. The preference for this type of sand is probably to be attributed to the slight roughing of the surface of the quartz grains by the deposit of iron oxide which affords a better attachment for the bonding material used.

In the region from St. Paul southward to Northfield, a distance of forty miles, the St. Peter formation is generally the bed rock. The glacial drift being thin in much of this area, numerous exposures of the St. Peter appear, usually as a soft yellow sand, or as friable sandstone. From Northfield eastward to the Mississippi along the valley of Cannon River the St. Peter formation is conspicuously exposed in the flanks of the flat topped, mesa-like hills and in the valley sides as white or yellow sand.

From Red Wing to the Iowa line the St. Peter is seen in the valleys tributary to the Mississippi at gradually lower and lower levels as one goes southward. The exposures are too numerous to warrant special description. The most characteristic feature of the sand is its uniformity in texture.

The Oneota and Shakopee dolomites, which occupy the interval between the Jordan and the St. Peter formations, also carry thin beds or lenses of sand or sandstone similar to the Jordan or to the St. Peter, but

such beds are usually pocket-like and rarely of commercial importance, except very locally.

A chemical analysis[5] of the St. Peter sandstone from Fort Snelling is as follows:

Silica, SiO_2	97.67%
Alumina, Al_2O_3	1.31%
Lime, CaO	0.41%
Potash, K_2O	0.02%
Iron, Fe_2O_3	0.55%
Soda, Na_2O	0.15%

A bank sample of the St. Peter sand, such as is used in foundry work, would probably show a considerably lower silica content, but samples from selected horizons of the cleaner sand show a silica content of 98 per cent.

The Decorah formation.—The Platteville limestone, Decorah shale, Galena limestone, and Maquoketa shale formations overlie the St. Peter sandstone and occupy the upper part of the Ordovician group of beds. The Decorah shale is extensively used in different parts of the state for making brick, tile, and terra cotta. It is of minor importance as a source of clay for foundry use because of the rather large percentage of fluxes usually present.

The Cretaceous formation.—As explained in the foregoing geological history a long interval of subaerial erosion and weathering immediately preceded the Cretaceous period, during which time the old crystalline rocks were deeply decomposed, the sedimentary rocks disintegrated, and the limestones leached of their readily soluble constituents. The feldspars of the crystalline rocks were kaolinized and in turn leached of much of their more soluble lime and alkalies leaving semi-refractory clays as a residuary.

The Cretaceous sea encroaching upon the land found great quantities of soft and loose products of rock-weathering ready for redistribution, and accordingly the deposits of the Cretaceous period consist of a great variety of materials derived from the acid and basic crystalline rocks and from the sandstones, limestones, and shales of the sedimentary formations.

In re-working this material the Cretaceous sea in some areas accomplished a remarkably complete separation of the coarse and fine materials, depositing beds of dense fat clays in certain localities, or at certain horizons, and clean, well-assorted sands in others. In other areas the separation was less complete or very poor and the products of rock-weathering were redeposited as poorly assorted clays and sands, or as alternating thin beds or laminations of these materials.

[5] Winchell, N. H., Geology of Minnesota Final Report, Vol. 1, p. 202, 1884.

The Cretaceous formation in general has suffered little alteration or induration since its deposition, so that the beds are still found in much the same condition as they were deposited. The sands are commonly loose, incoherent material, and friable sandstone. The argillaceous material appears as clays or soft shales.

The old rock floor on which the Cretaceous was deposited was marked in certain localities at least, by numerous small potholes and caves, in which the clays accumulated in the manner illustrated in Figure 1.

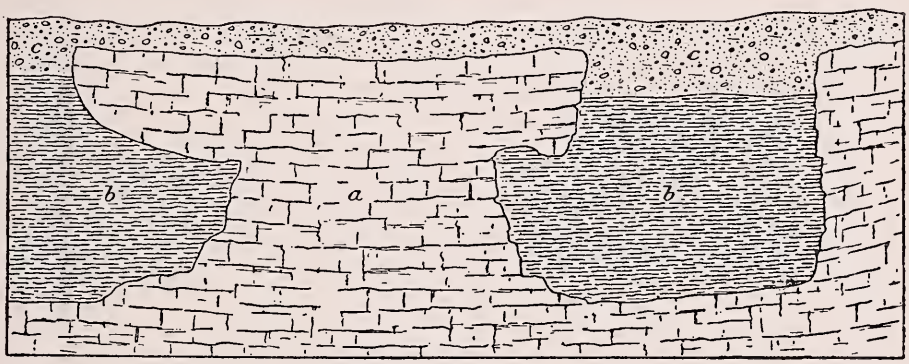

FIGURE 1. SECTION OF CRETACEOUS CLAY AT SOUTH BEND, (*a*) SHAKOPEE DOLOMITE; (*b*) CRETACEOUS CLAY; (*c*) DRIFT
AFTER N. H. WINCHELL

One of the important deposits of foundry clay worked in the vicinity of Ottawa, Minnesota, occurs in these relations in potholes in the basal portion of the Oneota limestone, and in the top of the Jordan formation, samples of which appear in Table XIII.

One of the largest deposits of Cretaceous clay in the state, at present worked as a source of clay for the Red Wing potteries, is found in Goodhue County in the vicinity of Bellechester and Clay Bank. This clay has been used to a limited extent only in foundry work, but merits more extended use, since it is semi-refractory and certain beds in the series are highly plastic. The clay here occurs as thin beds for the most part alternating with beds of sand.

The sands of the Cretaceous frequently consist of nearly pure quartz, but such beds are usually thin, and there is also a considerable variation in texture in the different horizons. In view of the fact that much better sand for foundry purposes is obtainable from the St. Peter and the Jordan formations, the Cretaceous formation does not warrant special consideration as a source of quartz sand.

The Cretaceous formation is the source of the most refractory clay in the state. Chemical analyses of these clays show the following composition. The localities from which the foundry samples were collected are the same as for those given in the following tables.

TABLE II. ANALYSES OF BUFF TO WHITE BURNING CRETACEOUS SHALES

	1	2	3	4	5	6	7	8
Silica	69.92	69.84	68.298	69.050	59.72	70.10	87.70	68.70
Alumina	17.39	23.07	18.266	18.830	30.00	16.99	7.24	18.04
Ferric oxide	1.68	.48	2.867	2.607	.....	Trace	Trace	1.53
Ferrous oxide								
Lime	.60	.11	.719	.296	.82	.....	.67	1.24
Magnesia	1.11	.14	.802	.622	.51	.....	.07	.56
Sodium oxide	.07	Trace	.81	1.066	.....	.....	3.17	.24
Potassium oxide	2.25		.60	1.461	.....	10.69	.49	5.28
Phosphorus oxide	.....	.....	.....	.....	.....	.....	.....	.09
Sulphur trioxide	.....	.....	....	.....	.....	.23	.....	.....
Titanium	.63	.....	.. ...	.....	.....	.....	.....	.....
Moisture	1.10	6.35	1.29	.898	10.34	1.98	Trace	1.40
Ignition	5.45	.....	6.155	4.912	.....	.....	Trace	.....
Total	100.20	99.99	99.807	99.742	101.39	99.99	99.34	97 08

1. Red Wing, Goodhue County. Clay sampled at stoneware plant. F. F. Grout, analyst.

2. Red Wing, Goodhue County. Analysis reported by J. H. Rich to Heinrich Ries.

3. Red Wing clay. Sample from Minnesota Stoneware Co., Red Wing, April 22, 1902. C. P. Berkey, analyst.

4. Red Wing stoneware clay, air dried. C. P. Berkey, analyst.

5. Ottawa. Ottawa Brick Co. Ries, Heinrich, Clays; their occurrence, properties, and uses, 1906. 6, 7, and 8. Minnesota Geol. and Nat. Hist. Survey Final Rept., Vol. 1, p. 438, 1884.

6. Near Mankato. Clay filling hollows in Shakopee dolomite.

7. Near Mankato (sec. 20). White clayey bed of considerable extent.

8. Near Mankato. Clay or shale between Shakopee dolomite and Jordan sandstone in L'Huillier Mound.

TABLE III. ANALYSES OF RED-BURNING CRETACEOUS SHALES

	1	2	3	4
Silica	63.65	61.32	58.14	73.34
Alumina	17.27	12.27	19.40	14.75
Ferric oxide	.....	3.62	5.52	5.45
Ferrous oxide	4.75	4.18	.....	
Lime	1.21	.99	.79	.28
Magnesia	.06	1.76	1.52	.05
Soda	.91	.42	.54	Trace
Potash	2.47	3.59	2.09	Trace
Barium oxide	.....	.05	.....	.....
Manganese oxide	.....	.27	.....	.....
Phosphorus oxide	.....	.27	.....	.....
Sulphur	.....	.19	.....	.....
Titanium oxide	.62	.66	.68	.....
Moisture	2.03	.....	2.10	.....
Loss on ignition	7.36	10.73	8.81	4.71
Total	100.33	100.32	99.59	98.58

1. Gray shale, west of Springfield. F. F. Grout, analyst.

2. New Ulm, Minn. Brick clay, U.S. Geol. Survey Bull. 60, p. 151, 1890. T. M. Chatard, analyst. A brick made from this clay is reddish brown, strongly sintered, somewhat fractured. Sample taken by John Lind on south bank of Cottonwood River on section line at river crossing, east of wagon-road crossing, south of New Ulm.

3. Clay sampled by A. Parker, of Brown Valley, Minn., just beyond the state line in South Dakota. F. F. Grout, analyst.

4. Red ochery clay, near Mankato. Minnesota Geol. and Nat. Hist. Survey Final Rept., Vol. 1, p. 438, 1884.

As explained elsewhere, however, in the description of the foundry loams, the Cretaceous beds frequently consist of an intimate mixture of nearly pure quartz sand and semi-refractory clay, the deposits at Bellechester being a case in point. For material of this type the Cretaceous merits consideration.

Glacial deposits.—From what has been said above it will be readily understood that the glacial deposits are extremely variable in character, physically, mineralogically, and chemically, therefore it is difficult to describe them briefly or to explain in what ways they are unsuited to certain purposes and well adapted to other purposes. In each of the succeeding periods of glaciation the ice picked up more or less of the older glacial material, mixed it with material newly derived, and redeposited it in great confusion.

With reference to the sands and foundry materials the glacial deposits of Minnesota may be grouped as follows: Moraines of Wisconsin drift from the north and northeast (red drift); moraines of Wisconsin from the northwest; outwash; and glacial lake deposits. These groups are based on differences in character and not strictly on origin, for example, the gray drift moraines include material deposited in two or three separate invasions of ice.

Moraine deposits.—Where the ice held its position for considerable time, the deposits laid down at the edge of the ice sheet are called moraines. These were deposited by the ice directly. Their topography is distinctive. The surface is characterized by sharp knolls and enclosed basins, by hillocks, and hollows, or by interrupted ridges and troughs, which may interlock in places and assume rudely parallel positions. The depressions are often without outlets and water falling into them forms marshes, ponds, and lakes where the material constituting their bottoms is sufficiently impervious to prevent its escape. The knolls vary in size, but are usually rounded at the top and have moderate to steep slopes. Variations in height of moraines are due to the unequal amount of material held by the ice at those points. The moraines are arranged in rudely concentric lines which mark successive positions of the border of each ice sheet as it was melted off from that region. For building and foundry purposes, it is only the "sandy moraines" that contain deposits of value.

Ice advanced over Minnesota from two directions. One lobe of the glacier came from the north and northeast, from the Lake Superior region and northern Wisconsin, traveling over rocks of the siliceous type, largely sandstones, quartzites, and crystalline rocks. The material brought to Minnesota by this lobe of the continental ice sheet was predominantly sandy and such clay as it contained carried relatively small amounts of fluxes such as lime, soda, and potash. This material is known as the "red drift," considerable deposits of which occur along the

eastern side of the state, from Minneapolis and St. Paul north. By careful selection material may be found in this red drift well suited for use as sand. Some is used for foundry work at Minneapolis. See Table XII, No. 254.

The other lobe of the glacier coming from the west and northwest brought much more limestone, clay, and shale—the gray drift. The deposits of sand are relatively few and impure. There is little material that can be used for foundry work.

Glacial loams.—Some of the loams in Minnesota are derived from moraine material. In creeping slowly over the region the glacial ice, 1,000 feet or more in thickness, with great quantities of rock incorporated in it, developed much movement within the mass itself. It served as a great mill in which the rock fragments were ground upon each other, much of the rock being reduced to fine silty material which has aptly been called "rock flour." During the warmer seasons of the year in glacial time, great streams issued from the ice margin carrying large quantities of this rock flour which was spread over the flood plains. During the colder seasons, with the diminishing of the flood waters, this silty rock flour became dry dust which was blown about by the winds and some of it was carried back over the glacier's margin and deposited on the surface of the ice itself. When the ice ceased to move and finally disappeared by melting, this silty rock flour was gradually let down and left as a blanket mantling itself indiscriminately over the knolls, hills, and intervening low areas of the terminal moraine, as well as over the ground moraine.

This silty rock flour was derived in part from the grinding up of partially decomposed feldspars, argillaceous limestones, and siliceous dolomites susceptible of further decomposition. Later, under the influence of superficial weathering, decomposition and leaching took place carrying away much of the soluble matter and leaving behind the more insoluble clay residuum, thereby changing the rock flour from a silty to a loamy consistency. More or less of the loams in Minnesota that are used in foundry work were derived in this manner. These loam deposits are variable in depth, in texture, in clay content, and in content of other minerals, and are irregular in distribution. A product uniform in character is hardly to be expected from this source, and an attempt to map these loams except in a very general way would encounter many perplexing problems.

Outwash deposits.—As the ice melted the water issuing from the edge of the glacial ice carried with it sand and gravel. These were spread over the plains in the form of alluvial fans. As the escaping waters continued to deposit sand and gravel, these fans united and formed outwash

plains. The outwash plains lie on the outer border of the moraines, and the sand and gravel composing them is sorted by the action of the escaping waters. Many outwash deposits may be traced up to a moraine, which marks the position of the ice border when they were laid down. Some show a decrease in coarseness passing away from the moraine, the coarse material having been dropped close to the edge of the ice and the fine carried a greater distance.

The waters found themselves in valleys, over which they spread. Carrying loads too great for their velocity, they aggraded their valleys and built up large valley trains. At the maximum of their discharge, the outwash deposits consisted of sand and gravel. They extend far beyond the unstratified drift with which they are associated. They supply by far the greater portion of the sands used for structural work in Minnesota, and also much foundry material.

A type of loam differing slightly from that formed in the weathering of sandy moraines is derived from the sandy flood plains of glacial streams. Probably the broad flood plains supported some vegetation and received deposits of sand and rock flour only at time of flood; so that the sand is mixed with vegetation as well as partly weathered. Some such deposits of loam are many feet thick. By reason of their mode of formation, they are likely to be more uniform in composition and depth than the loams of morainic deposits. This type of loam is therefore most promising for foundry material.

The loam on the old flood plains has been subjected to the same process of superficial weathering as the moraines; that is, it has decomposed and leached to some extent, as a result of which the upper one to three feet is frequently heavier, or more clayey, than that below, which must be taken into account in pitting it for foundry use.

Much of the loam referred to underlies good agricultural land. It is possible to recover the loam without destroying the soil. If the upper portion of soil is moved by wheel scrapers and spread again over the floor of the pit after the foundry loam is removed, the land is still of full value for agricultural purposes. Loam can be removed in this way at a very low cost without injury to farm lands. A similar method has been used in the Red River Valley in working some clay deposits. The method is employed in New Jersey to win foundry loams of exactly the type here described.

The sands above described as occurring on glacial flood plains do not all border streams at present, for the streams that built these ancient plains in many instances became extinct with the glacier. The old flood plains are not infrequently far removed from present drainage lines, or if they are near present drainage, they may or they may not bear definite relation to present drainage.

Lake beaches.—In the northwest part of the state, in the region of glacial Lake Agassiz, there is a shortage of all kinds of sands. The sands of this region are secured from ridges of sandy gravel formed along the shores of extinct lakes at successively lower levels, down to existing lakes. These ridges are known as "lake beaches," and are the result of sorting by wave action.

Loess.—In the southeastern part of Minnesota from the vicinity of Red Wing to the Iowa line there is a belt of country bordering the Mississippi River about 30 miles wide and 100 miles long, in which a fine silty loam known as loess occurs at many places. The distribution of the loess is shown in a general way in Figure 2.

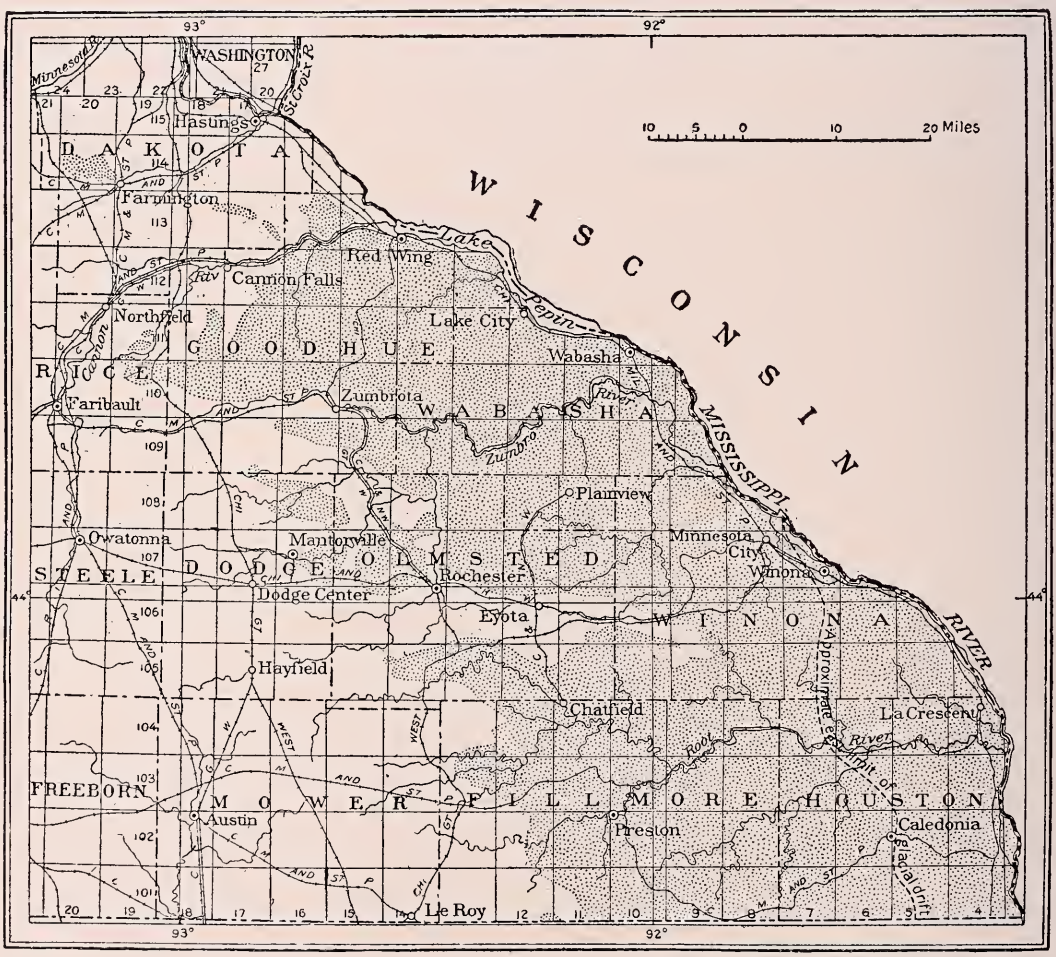

FIGURE 2. MAP OF SOUTHEASTERN MINNESOTA SHOWING AN AREA (DOTTED) IN WHICH THE DRIFT IS LARGELY COVERED WITH LOESS. THE LOESS MANTLE IS NEARLY CONTINUOUS EXCEPT ALONG THE LARGER VALLEYS
AFTER FRANK LEVERETT

The loess is of interest to the founding industry as a source of molding sand for brass, other alloys of copper, aluminum, etc. Most of the brass sand imported by the foundries of Minnesota from Missouri, Illinois, and Kentucky is simply loess such as may be had in southeastern Minnesota at hundreds of places.

The loess occurs in the area shown in Figure 2 up to 40 feet in depth, and possibly deeper. It is not limited by any altitudes in this area, but occurs capping the highest hills, bluffs, ridges, and uplands 500 feet or more above the Mississippi, as well as in the valleys down practically to the river level. A typical example of loess is to be seen at Red Wing capping Barn's Bluff which is a small isolated hill rising with abrupt slopes, and sheer cliffs to about 400 feet above the river. The loess, at least 20 feet in depth, caps the highest part of this hill. It occurs also in the vicinity of Red Wing mantling the terraces 40 feet above the Mississippi and back from the main stream in the side valleys at all levels to points 400 feet above the river.

Some of the loess at low levels has been derived from the upland loess and washed down by streams, but part of it was originally deposited at the lower elevations.

On the whole the loess on the uplands 200 to 500 feet above the Mississippi is more uniform in texture and mineral composition than the loess in the valleys. In deep fresh exposures the loess is usually pale blue-gray in the lower portion, pale yellowish gray in the middle portion, and brown or yellowish brown in the upper one to three feet. There is an appreciable difference usually in the texture of the material accompanying the difference in coloring; that is, the basal portion of bluish tint is more silty, the central portion more loamy, and the surface portion clayey. The difference in coloring and texture appears to be due to progressive weathering rather than to a difference in the original deposition.

Owing to the great abundance of the material and its accessibility to the railroads it is unnecessary to describe in detail the numerous exposures. At Clay Bank station, south of Red Wing, the Chicago Great Western Railroad has made a cut about 8 feet deep through the loess and the material could be loaded there with steam shovel. Other deposits of the same material similarly situated with reference to railroads could no doubt be found so that for foundry needs a practically unlimited supply can be had at nominal cost.

The following analysis shows that the loess carries about 13 per cent of iron, alkali, and alkali earth compounds, which would insure a low fusion point, but since the temperatures of the melts of brass and its alloys are low there is no danger of fusion of the loess when used as molding sand for these metals.

The texture of the loess is indicated by the mechanical analyses of Table XI. A chemical analysis is stated below:

CHEMICAL ANALYSIS OF LOESS (BY F. F. GROUT)

Silica	71.53
Alumina	8.07
Iron oxide	5.63
Magnesia	1.74
Lime	2.36
Soda	1.85
Potash	1.97
Ignition	4.50
Water	2.30
Titanium oxide	.31
	100.26

As to the origin of the loess there has been much difference of opinion, some investigators claiming a wind origin and others a water origin. Probably both agencies have been active. Undoubted evidence of water stratification in the loess is to be seen in certain localities even on the uplands 500 feet above the Mississippi River; and at other localities equally conclusive evidence of wind work is to be found. There has, no doubt, been more or less redistribution of the loess by both wind and water since its original deposition.

The glacial rock flour, above described, may have been the chief source of the loess, but the fact that the impure dolomites of the region upon weathering leave a residuary product of closely similar constitution suggests that this also may have been a source.

Recent deposits.—The sands of the recent period used in Minnesota belong to two classes, lake sand and river sand. Most of the lake sand can be used for building purposes, and may be used in some foundry work. An extensive plant is operating at Duluth where the sand is obtained from Lake Superior.

A type of loam is found mantling the terraces in the valleys of streams at levels of 20 to 200 feet above present streams. In mode of origin these loams are not unlike the glacial outwash loams. In fact some of them are genetically the same. Others, however, were formed in a similar manner but at a later peroid; that is, they were deposited by the streams that in postglacial time have passed through the stages of aggradation and degradation. Generally these loams are variable in character, but afford good foundry material if sufficient care is exercised in choosing the localities and in pitting the material.

TABLE IV. LIST OF MINNESOTA FOUNDRIES AND LOCALITIES SUPPLYING THEM WITH FOUNDRY SAND

	Brass Sand	Molding Sand	Core Sand
Albert Lea			
American Gas Machine Co.		Outside state	St. Peter, Minneapolis
Austin			
Austin Foundry		Lime Springs, Ia.	Local
Brainerd			
Parker and Topping Co.		Kerrick	Coarse, local
		St. Paul	Fine, St. Peter, Minneapolis
Chaska			
Ess Bros.		Minneapolis	Minneapolis
Cloquet			
Cloquet Foundry		Local	Local
Crookston			
Crookston Iron Works		Kerrick	Local, glacial
Duluth			
Clyde Iron Works		Kerrick	Fine, St. Peter, St. Paul
			Coarse, Lake Superior
Duluth Brass Works		Whitehead Bros., Buffalo, N. Y.	Whitehead Bros., Buffalo, N. Y.
Duluth Foundry and Faucet Co.		Albany sand	
Duluth Iron Works	Local	Kerrick	Coarse, Lake Superior
			Fine, St. Peter, St. Paul
Minnesota Radiator Co.		St. Paul	Lake Superior
National Iron Company		Kerrick	St. Peter, St. Paul
Fairmont			
Fairmont Gas Engine Co.		Waterloo, Ia.	St. Paul
Faribault			
Faribault Machine Shop		Local	St. Peter, local
Winter and Co.		Local	St. Peter, local
Nutting Truck Co.		Local	St. Peter, local
Fergus Falls			
Fergus Falls Iron Works		St. Paul, Kerrick	Local, glacial
Hibbing			
Oliver Mining Co.	Chicago	St. Paul	Local, glacial
La Crescent			
Smith Grubber Co.		Local	Local
Lake City			
Gillett-Eaton and Squire Co.		Local	Local
Mankato			
Little Giant Co.		Local	St. Peter, local
Mankato Mfg. Co.		Local	St. Peter, local
New Prague			
New Prague Foundry Co.		Mankato	Mankato, St. Peter
Ortonville			
Ortonville Foundry		Big Stone City, S. D.	Local, glacial
Owatonna			
New Owatonna Mfg. Co.		Faribault	St. Peter, Faribault
North Star Iron Works		St. Paul	St. Peter, Faribault
Paynesville			
C. W. Peavey		Local	Local, glacial
Red Wing			
Red Wing Iron Works		Local	Local
St. Cloud			
Granite City Iron Works		Minneapolis	St. Peter, St. Paul
St. Cloud Iron Works		Kerrick	St. Peter, St. Paul

TABLE IV—*Continued*

	Brass Sand	Molding Sand	Core Sand
Thief River Falls			
Thief River Falls Iron Works		St. Paul, Kerrick	Local
Virginia			
Virginia Foundry Co.		Kerrick	Biwabic, glacial
Winona			
Gate City Iron Works		LaCrosse, Wis.	Minneapolis
New Winona Mfg. Co.		Rockford, Ill. Minnesota City	River, local
Winona Machinery and Foundry Co.		Minneapolis	Jordan, Ottawa
Minneapolis			
American Brake Shoe Co.		Local, glacial	
Crown Iron Works		Local, glacial	
Commutator Co.	Albany, N. Y.		St. Peter, local
Eagle Foundry		Local, glacial	Glacial, local
Flour City Ornamental Iron Co.	Milwaukee, Wis. France		St. Peter, local
Gas Traction Foundry	St. Louis, Mo.	Local, glacial	Steel, Jordan, Ottawa
Mpls. Steel and Mach. Co.		Local, glacial	
Soo Line Railroad Shops	Albany, N. Y.		St. Peter, local
University of Minnesota Foundry	Albany, N. Y.	Local, glacial	St. Peter, local
St. Paul			
American Hoist and Derrick Foundry	Albany, N. Y.	Local, glacial	Steel, Ottawa St. Peter, local
Herzog Foundry	Local, glacial		
Northern Malleable Iron Works	St. Louis, Mo. Fort Snelling		
Union Brass Works	Monmouth, Ill.		
Valley Iron Works		Local, glacial	
St. Paul Foundry Co.		Local	

LABORATORY METHODS OF TESTING FOUNDRY SANDS, LOAMS, AND CLAYS

Mechanical analysis of sands, loams, and clays.—The mechanical analysis of a sand or loam, as generally understood, consists simply in separating the material into a series of products graded according to size of the grains and weighing these products to determine the percentage of the coarse and the fine material present. There are many ways of sizing, but most of those in general use are modifications of two well-known methods: (1) by using a set of screens, in which the material is separated dry into a series of products ranging from coarse to fine, and (2) by the use of water so that the different sized grains in the material are separated from each other by their buoyancy. The former is commonly called the dry method, and the latter the wet method. The two methods are frequently combined and there is almost no limit to the degree of refinement to which either method may be carried.

The sizing of sands by means of a set of screen sieves is employed universally where sands are used in the various industries and the value of a given sand, or its adaptability for a certain purpose, is based to a greater or lesser degree on the results shown by the screen analysis.

The dry screen analyses of the molding sands were made in the ordinary way, using a set of standard 6-inch screen sieves of 4, 10, 20,

30, 40, 50, 60, 80, 100, and 200 meshes to the inch. The 30- and 50-mesh screens were used only in special cases. The sand samples for analysis, consisting of 50 grams (about 2 ounces), were previously dried in a sand bath at a temperature of 100° C. for 24 to 48 hours, or until they eased to lose weight, after which the samples were pulverized in an iron ıortar with a rubber shod pestle to break up the clusters without breaking the individual sand grains. The screens were shaken by hand, using, one, two, or more screens at a time, as conditions warranted. In some instances a small stiff bristle brush was used on the screens to hasten the passage of the sand through the screen, since with some samples no reasonable amount of shaking or jarring would pass the sand without the aid of a brush. A mechanical shaker operated by an electric motor was tried, but found impracticable, since uniform or complete separations generally could not be obtained.

The screens were calibrated in the physics laboratory of the University of Minnesota by the aid of an optical micrometer, with the results shown in Table V.

TABLE V. SIZE OF SCREEN OPENINGS AND DIAMETER OF WIRE IN SCREENS

Mesh of Screen	Diameter in Inches of Wire in Screens According to Manufacturer	Size in Inches of Opening of Screens According to Manufacturer	Size in Inches of Opening of Screens Found by Actual Measurement
4	.065	.185	.185
10	.035	.065	.074
20	.0172	.0328	.0341
30	.0135	.0198	
40	.01	.015	.0189
60	.008	.0087	.0096
80	.0057	.0068	.0074
100	.0045	.0055	.0062
200	.0021	.0029	.0038
220	.0017	.0028	
240	.0016	.0026	
260	.0016	.0022	
280	.0016	.002	
300	.0016	.0017	

In ordinary sands the grains are more or less coated by a film of clay which in the fine sizes materially increases the actual diameter of the grains. In sands where silty material is present in appreciable amounts together with 2 to 10 per cent of clay, the silt grains are cemented to the coarser grains of sand by the clay film in greater or less amounts which still further increases the actual diameter of the sand grains. Both the silts and the finer sizes of sand are gathered in clusters, or compound grains, particularly in loamy sands, and these clusters function as unit masses, and in the ordinary screen analysis appear as individual grains in the various sizes.

The purpose of pestling dry sand is to break up these clusters, free the sand grains from adhering finer material, and bring the material into a state of individual particles. In some sands, and in loams generally, however, no ordinary amount of pestling in the dry state will completely break up the clusters or remove the adhering silt grains, much less will pestling remove the clay coating from the grains of sand. Hence it is impossible to obtain a true sizing of the material by the dry method. The common screen analysis, while valuable because easily made and because it shows in a general way the physical constitution or texture of the sand, is at best a proximate analysis only.

Inasmuch as clay in molding sand performs an important function as bonding material, it is essential that a determination as accurate as possible be made of the clay present in the different molding sands, and accordingly the following procedure, adapted from one of the common methods of soil analysis, was employed.

A 50-gram sample of the sand to be tested was taken in the same manner as for a dry screen analysis; that is, the sample was weighed out after thorough drying in the sand bath. The sample was transferred to a common 8-ounce nursing bottle. Six ounces of distilled water and 5 cubic centimeters (about one teaspoonful) of ammonia, were added, making the bottle about half full. The bottle was placed horizontally in a mechanical shaker, shown in Figure 3, and shaken for five hours; the purpose being to free the sand grains of any coating of clay and to deflocculate the clay.

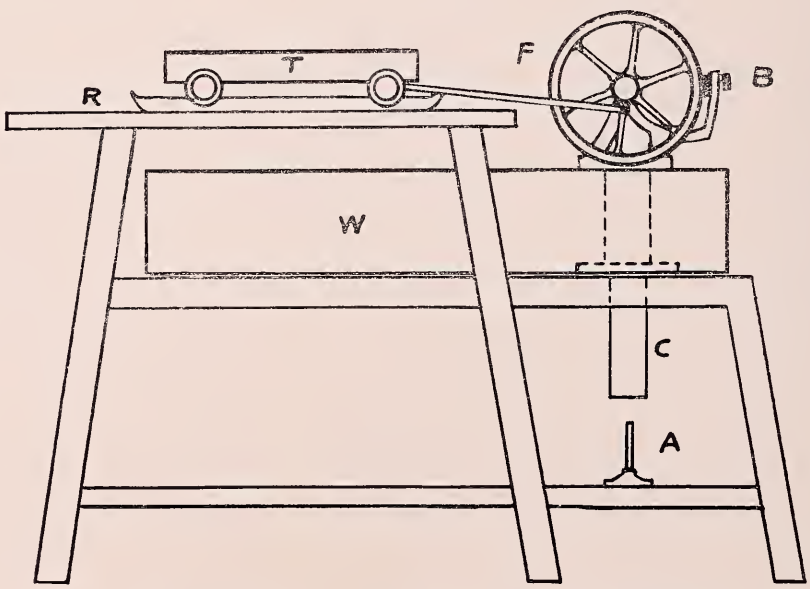

FIGURE 3. HOT AIR ENGINE USED FOR SHAKING BOTTLES IN CLAY DETERMINATIONS

The shaker was propelled by a small hot air engine. The cylinder *C* about 2 inches in diameter by 12 inches long, was thin walled. The upper part was surrounded by a tank of water *W* to prevent excessive heating. Heat was supplied at the lower end by a Bunsen burner *A*, the amount of heat being controlled by the supply of gas, this in turn determining the speed of the engine. The engine would run for hours without attention. The length of stroke of the engine piston was about 2 inches. The tray *T* carried 12 bottles and moved horizontally on the track *R*. The flywheel *F* ran about 40 revolutions per minute. The length of stroke of the pitman from the flywheel to the tray was about 3 inches.

Immediately after shaking, the contents were washed into graduated glass cylinders about 13 inches tall and 1⅞ inches in diameter which were allowed to stand at room temperature for 24 hours. The material that remained in suspension after 24 hours was considered clay. The water with clay in suspension was siphoned off into large beakers, after which the sand in the cylinder was again agitated by jetting distilled water under pressure into the sand; then the cylinders were allowed to stand again for 24 hours. This process was repeated until the cylinders showed nothing in suspension on standing for 24 hours.

The material obtained from these 24-hour decantations, designated clay, was precipitated in the beakers by adding a small amount of barium chloride, for in most cases the clay would not settle out completely by gravity. This clay was recovered, dried, and weighed, thus giving the percentage of clay in the sample which might be regarded as acting as the bond for molding purposes.

The contents of the cylinders, after removing the clay, were again agitated with distilled water and allowed to stand for 30 minutes. The water, with what was in suspension, was siphoned off, or decanted, at the end of 30 minutes, this process being repeated until nothing remained in suspension for the 30-minute period. The material from these 30-minute decantations, called "thirty minute silt," was recovered, dried, and weighed.

In the same manner a 15-minute silt was separated, recovered, dried, and weighed, after which the contents of the cylinders, regarded as true sand, were recovered, dried, and weighed, and then subjected to the usual mechanical dry screen analysis, using the screen sieves.

This combination of wet and dry methods of analysis shows the percentages of clay, 30-minute silt and 15-minute silt, present in the sample and the percentage of 4, 10, 20, 40, 60, 80, 100, and 200-mesh sand present after removing the clay and silts, making 11 separates in all.

In the course of the laboratory work on foundry sands, 320 samples of sand, loam, and clay were subjected to the common screen analysis, following the dry method above described. Two hundred sixteen of these

samples were subjected to the combined wet and dry method of analysis. In the various tables where the results of these analyses are recorded, the dry method analyses are referred to as "A" and the analyses by the combined method, showing the percentage of clay and silt, are referred to as analyses "B."

Comparison of wet and dry methods of analysis.—A comparison of the results of these two methods of analysis of the same materials brings out many facts in connection with the texture of sands. Illustrating the marked difference in results by the two methods, the results of analyses of three samples, 9, 3, and 18 are given in which analysis "A" and "B" in each are duplicate samples of the same material. These examples are fairly representative of the entire series.

TABLE VI

Mesh of Screen	Sand No. 9		Sand No. 3		Sand No. 18	
	A	B	A	B	A	B
4— 10			.20		1.00	.20
10— 20	.80	.74	.82	.86	.20	.30
20— 40	43.50	22.80	6.63	5.74	.70	.60
40— 60	29.00	26.06	18.34	14.10	1.00	.54
60— 80	17.00	25.08	6.20	6.08	1.50	2.32
80—100	4.50	10.00	4.64	4.22	6.00	3.38
100—200	1.00	7.44	16.90	10.98	29.70	22.82
200-silt	2.00	3.50	43.32	38.00	59.50	53.48
15-minute silt		.12		2.00		1.90
30-minute silt		1.40		6.00		7.00
Clay		2.00		10.80		7.00
Total	97.80	99.14	97.05	98.78	99.60	99.54

Sample 9 is a quartz fire sand, 3 is a common loam, and 18 is a brass sand. Notwithstanding all the samples for analyses "A" were thoroughly pestled, there still remained clusters or aggregates of grains that did not break up into individual particles. These clusters did break up by treatment with ammonia in the analyses "B."

It is to be noted that different sands and loams behave very differently with respect to the clustered grains; that is, some samples yield to pestling readily while others do not, so that there is no uniformity in results, thus the sizing obtained by the dry method of analysis is not to be depended on even in sands with a small clay content, as sample 9 shows.

The primary purpose in the wet method analysis was to determine the percentage of clay present in the various sands, loams, and so-called clays used in foundry work, the assumption being that such clay afforded the bond essential to molding sand. But this method of analysis also provides two silt determinations; that is the 15-minute and 30-minute silt, the

grains of which are intermediate in size between the 200-mesh screen and the clay. Such experiments as were undertaken indicate that these silts play an important rôle in the permeability of the sand by their behavior in granulation. They are important also in connection with the tensile trength developed in the molds, both in the green and in the dry sand.

Perfect sizing was not attained in the wet analysis "B" because the method employed involved two essentially different principles in the separation. That is, the silt separations relied on the suspension of the particles in water, which in turn depended on the specific gravity of the individual particles and not on their mass or diameter, whereas the sizing of the sand after the silts and clays were removed, using the sieves, depended on the diameter of the grains only.

As a check on the method of sizing, the silts obtained in the analyses "B" were examined under a microscope, using a scale to measure the diameter of the silt grains. While, as was anticipated, many large grains were found in the silts, some even larger than the openings in the 200-mesh screen, still the percentage of such grains was small, and the bulk of the material, both in the 15- and the 30-minute silt, was fairly uniform in size. These measurements showed that the average diameter of the grains in the 15-minute silt was .00053 inch and the average diameter of the grains in the 30-minute silt was .000236 inch. That is, the diameter of the 30-minute silt grains was a little less than half that of the 15-minute silt, indicating a fair degree of sizing by water suspension.

The openings in the 200-mesh screen, as shown in Table V, were .0038 inch; and while no attempt was made to measure, or otherwise determine the size of the clay grains, numerous workers in soil analysis have given the diameter of clay grains as "under .000197 inch." From which it will be seen that there is a rather wide interval between 200-mesh sand and clay, of which heretofore no account has been taken in ordinary molding sand analyses. The determination of the percentage of 30-minute and 15-minute silts present in the various materials makes possible a more critical comparison of the samples as to their texture and permeability.

Comparing analyses.—To facilitate comparison of analyses a factor was sought that would express in a general way the comparative fineness of the individual sample as indicated by the screen analyses. Such a factor is recorded in the tabulated analyses.

The diameter of the sand grains in any of the separates obtained by screening naturally varies from the size of the opening of the screen through which the sand passes to the size of the opening of the next finer screen on which the sand is caught. The average grain in each of the separates may be taken as the mean between the openings. For example, the openings in the 40-mesh screen were found to be .0189 inch and the

openings in the next finer screen, viz., 60-mesh, .0096 inch. The mean between these two is .01425 inch and the average or mean sized grain of the 40- to 60-mesh sized sand is taken to be .01425 inch in diameter. Determining the mean or average diameter of the other separates in the same manner gave the results shown in the following table.

TABLE VII

Mesh of Screen Used in Sizing Sands	Average Diameter of Sand Grains in Sized Sands
4—10	.1295 inch
10—20	.054
20—40	.0265
40—60	.01425
60—80	.0085
80—100	.0068
100—200	.0050
200-silt	.00216
15-minute silt	.00053
30-minute silt	.000236
Clay—below	.000197

The diameters of the 15- and 30-minute silts were determined by measuring the silt grains themselves with a microscope. The diameter of the clay grains was taken from tables published by workers in soil analysis.

The method of computing the fineness factor, or comparative grain, was to multiply the average diameter of the grain in each separate by the percentage of the separate present in the sample and divide the sum of the products so obtained by the sum of the percentages of the several separates.

For example, brass sand 18, taken from Table XI, computed for grain and mesh, gives the following results:

TABLE VIII

Mesh of Screen	Average Diameter of Sand Grain in Each Separate		Proportion of Each Separate Present		Product of Per Cent Multiplied by Average Diameter of Grain
4— 10	.1295	×	.002	=	.000259
10— 20	.054	×	.003	=	.000162
20— 40	.0265	×	.006	=	.000159
40— 60	.01425	×	.0054	=	.000076
60— 80	.0085	×	.0232	=	.000197
80—100	.0068	×	.0338	=	.000229
100—200	.0050	×	.2282	=	.001141
200-silt	.002165	×	.5348	=	.001157
15-minute silt	.00053	×	.019	=	.000010
30-minute silt	.000236	×	.07	=	.000016
Clay	.000197	×	.07	=	.000014
			.9954		.003420

$\frac{.003420}{.9954}$ = .0034 inch, the comparative diameter of grain. The comparative mesh computed by this method is an approximation only. Greater accuracy would have been obtained if the number of grains of

sand in a unit volume for the different separates had been computed and used as a factor in computing the comparative mesh.

The comparative mesh was obtained by interpolating the comparative diameter of grain in the scale of screen openings given in Table V (page 33). Interpolating .0034 inch in the scale of screen openings, it was found to correspond to a mesh of 216 (see Fig. 13). Accordingly 216 is taken as the comparative mesh of this sand.

Laboratory tests for bonding power of sands, loams, and clays.— In testing the bonding power of molding sands the usual method employed in testing cement for tensile strength was used. This consists in making a briquet of the material to be tested having a cross section of one square inch in the center and larger at the ends, as illustrated in Figure 4, *A, B,* and *C*. The briquets were broken in the apparatus, Figure 5, by

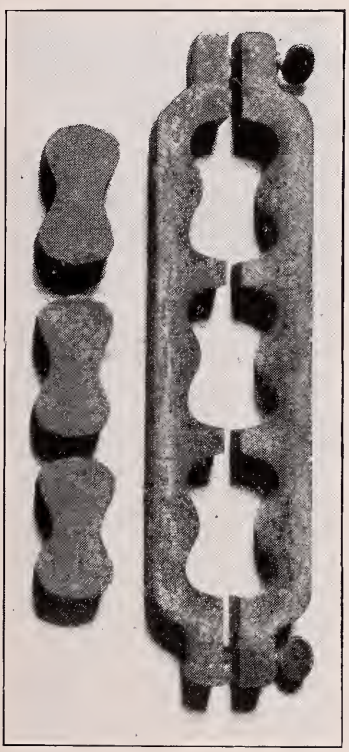

FIGURE 4. BRASS MOLD FOR MOLDING SAND BRIQUETS FOR TENSILE STRENGTH TESTS

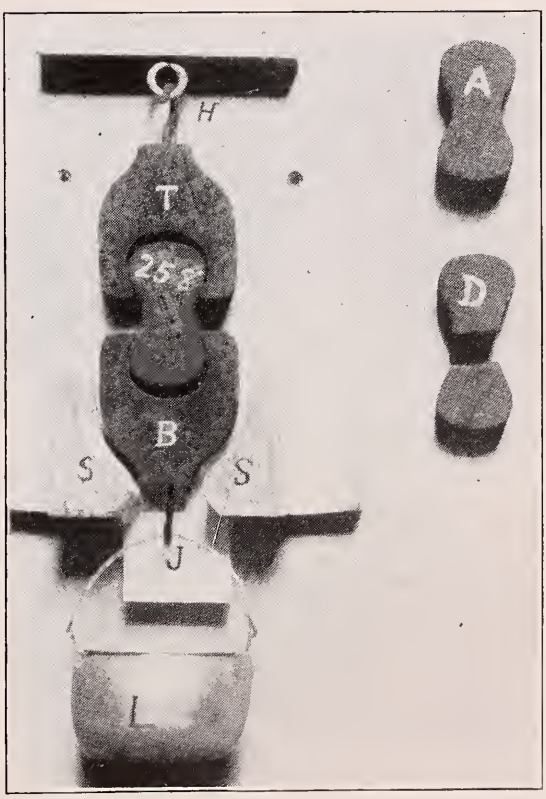

FIGURE 5. APPARATUS FOR BREAKING BRIQUETS OF MOLDING SAND TO DETERMINE TENSILE STRENGTH

applying a load at the lower end of the briquet and measuring the stress, in pounds or ounces, required to break the one-square-inch section. The results give the tensile strength of the molding sand in pounds per square inch. In making the briquets the molds, shown in Figure 4, were used and the molding sand was rammed into them, following the approved methods

of foundry practice in tempering the sand and tamping it into the mold.

The briquets were run in series of three, designated series A, B, and C, with three briquets in each series. The three briquets in series A were broken at once upon taking them from the molds to determine the tensile strength of the damp or green sand, taking the average of the three tests. The three briquets in series B were allowed to stand in the open air 24 to 48 hours for room drying, after which they were broken to determine the tensile strength of sand comparable to that of air-dried molds in foundry practice. The three briquets in series C were kiln dried, or furnace burned, as circumstances might suggest, at temperatures ranging from 400° C. (752° F.) to 1000° C. (1832° F.) after which they were broken and tensile strength noted.

In view of the fact that green molding sand rarely develops a tensile strength of more than a few ounces to the square inch, whereas the machines for testing cement briquets are not sensitive to such light loads, it was obvious that these machines could not be used for breaking the molding sand briquets, so special apparatus had to be devised for that purpose. A pair of jaws (Figure 5 *T* and *B*) were made of mahogany and provided with a mounting so that the briquets could be suspended vertically and the load applied directly to the lower end. This apparatus was sensitive to a breaking load of 2 ounces and gave satisfactory results up to loads of 100 pounds.

The upper jaw was suspended at *H,* by means of a hook and eye, and the lower jaw was carried by the briquet itself; thus forming a couplet that swung free and eliminated all torsional stresses. A bucket *L* was suspended on the hook *J* to receive the load, which consisted of water that was run into the bucket *L* by means of a rubber tube and pinchcock.

In measuring the breaking load everything below the breakline was counted; that is, the bucket *L* with its contents, the lower jaw *B,* and the lower half of the briquet carried by the jaw *B* were weighed and counted as breaking load. The blocks *SS* served to catch the jaw *B* when the break occurred so that there was no loss by spilling the water.

Green briquets weighed from 95 to 120 grams, or about 3 to 4 ounces, and in this method of testing the strength, about half of the weight of the briquet itself, was counted as initial load, and this was the measure of the sensitiveness of the apparatus; that is, if the briquet broke of its own weight its breaking strength was figured as one half of the weight of the briquet itself, or something less than two ounces.

For heavier loads larger buckets were used in the place of bucket *L* and bird shot, such as is used in ordinary cement briquet-breaking machines, was employed as load.

Determining the porosity of foundry sands and loams.—By porosity of a sand is meant the voids or interstitial space between the sand grains or the granules. It is the space unoccupied by solid matter, but occupied by air or water. The porosity of a sand is usually expressed in percentages of the volume of the mass. If a sand has a porosity of 30 per cent, it means that the sand grains occupy only 70 per cent of the actual volume of the container, and the remaining 30 per cent is vacant space or is occupied by air.

The test for porosity of the sands consisted in comparing the weight of a standard volume of each sample with the weight of the same volume of solid non-porous rock.

The standard volume used in the porosity tests was a brass cylinder 3 inches deep by 2 13/32 inches in diameter (Fig. 6 *V*), which was obtained by cutting a section from standard rolled brass tubing. This volume of water at ordinary room temperature weighed 228 grams. The average specific gravity of the rocks of the earth is 2.6 to 2.7. Ordinary molding sand is simply the fragments and weathered products of such rocks, and the numerous determinations made by many independent workers in soils and cement, and investigators of rock-weathering, show that common sand has a specific gravity essentially the same as average rock, viz., 2.65. The variations in specific gravity for the different types of sand are so slight as to be negligible. The specific gravity of the "fines" is slightly higher than for the coarse constituents, so that we have assumed a specific gravity of 2.7 as probably as near the truth as it would be possible to get even if precise determinations had been made. Multiplying 228, the weight of the standard volume of water, by 2.7 gives 615.6 grams as the weight of this standard volume of non-porous rock.

The standard volume brass cylinder was filled in turn with each of the sands after they had been dried in the sand bath for 24 hours, and a standard method of jarring the cylinder was used to compact the sand, following the method described by King.[6]

In making the porosity tests on molding sand the method of King was modified slightly as follows: A section of brass tubing (Fig. 6 *D*) the same diameter as the cup (Fig. 6 *V*) and 1½ inches high, was placed on top of the cup, held in position by a band. This section was filled with sand, thus adding a head of 1½ inches to the receptacle. It was found that more uniform results could be obtained in compacting the sand by this means.

[6] King, F. H. Principles and conditions of the movements of ground water: Nineteenth Annual Rept. U.S. Geol. Survey, 2, p. 208, 1899. Some of the preliminary laboratory work in determining the porosity and permeability of the sands discussed in the treatise above mentioned was done by the writer in 1897 under the direction of Professor King.

The method of compacting the loose sand, as described by King, consists in holding the cup filled with sand firmly on a rigid table, preferably a stone slab, with one hand, and jarring the cup with the other hand by tapping it with a piece of wood, turning the cup part way around from time to time; the tapping of the cup being vigorous enough to disturb the sand grains and allow them to rearrange themselves.

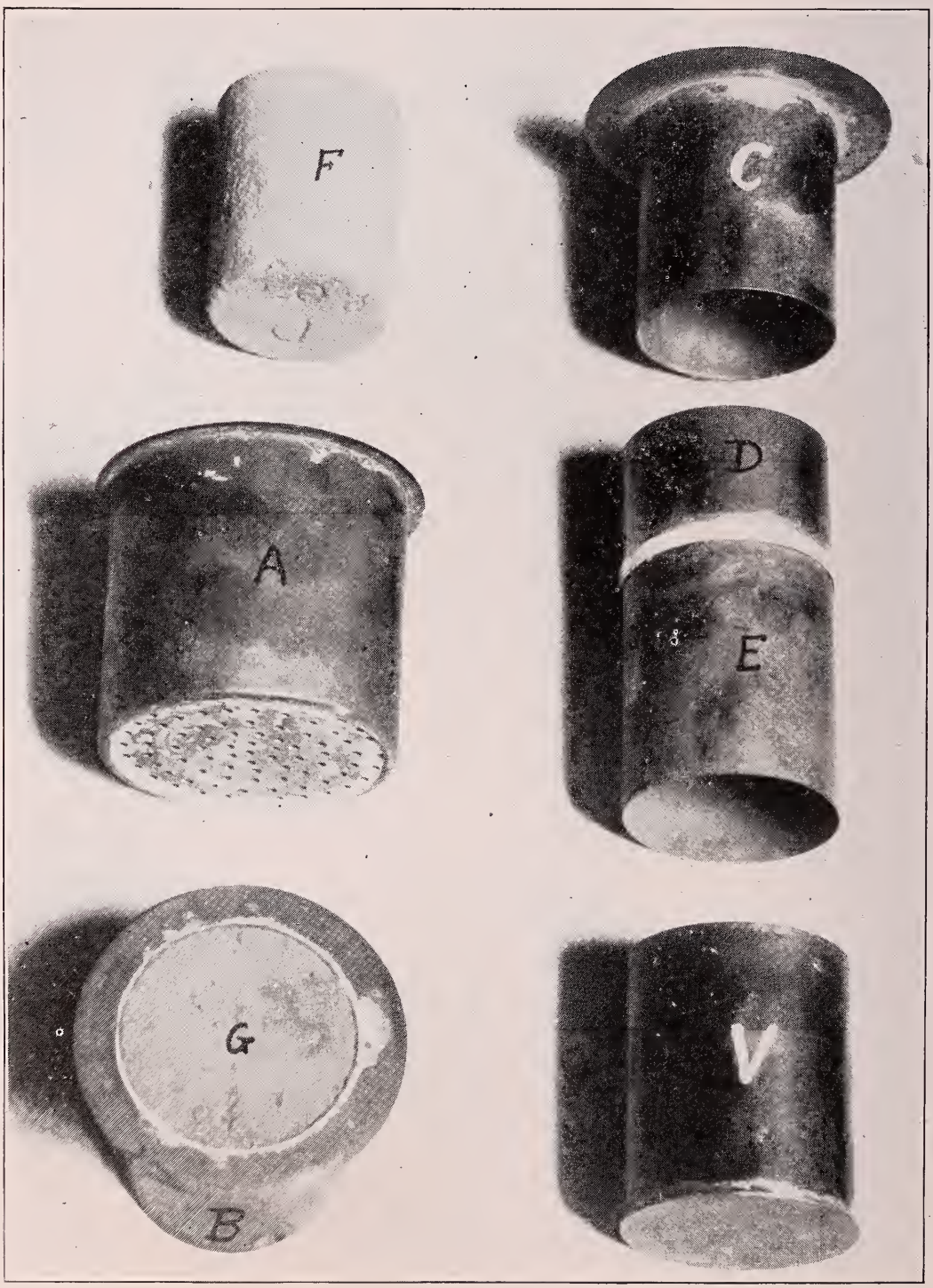

FIGURE 6. BRASS CYLINDERS USED FOR MOUNTING CORES OF MOLDING SAND FOR PERMEABILITY TESTS; AND CUP *V* USED IN POROSITY DETERMINATIONS

After the sand had settled as much as it would by jarring, the extra section was removed from the cup, the top of the cup was stricken off with a metal straight edge, and the cup and contents weighed. Subtracting the net weight of the sand in the cup from 615.6, the weight of the same volume of solid rock, and dividing the difference by 615.6 gives the pore space in the sand in percentage of volume.

Other methods of determining the pore space were tried, such as adding sand to a measured volume of water and noting the volume of water displaced by the sand, but the results were unsatisfactory because of entrained air.

More refined methods of determining the pore space did not seem warranted because the per cent of pore space in sand is not a dependable measure of the permeability. Even in loose clean sand the permeability can be judged only in a very general way from the porosity, and in damp loams where granulation takes place there is no necessary relation between the actual porosity and the observed permeability. Permeability on the other hand is of vital importance, and this was determined directly by testing the sand without reference to its porosity.

The porosity of a large number of dry sands was determined by the method above described; that of the damp sands and cores was computed from the known weight, volume, and other factors; and the results appear in the various tables throughout the report. The porosity determinations included in the tabulations show that the permeability commonly is independent of the porosity.

Testing the permeability of molding sands.—Permeability of sand is the facility the sand offers to the passage of a liquid or gas through it. Permeability in sand is usually measured by the time required to pass a given volume of air through a column of sand of known dimensions.

For testing permeability, apparatus was designed and built that would deliver 74 liters of air at a constant pressure of 50 inches of water. In some respects this apparatus was adapted from the aspirator used by King.[7] A standard column of sand 2 13/32 inches in diameter and 3 inches high was used in all permeability tests. The time required to pass the 74 liters of air through the columns of sand was measured by a stop watch, which could be read to a fraction of a second.

One hundred eighty samples of sand and loam were tested for permeability with this apparatus, and an average of six runs was made on each sample. The time of passage of the air ranged from 24 seconds to 4,646 seconds in the different samples. The pressure of the air remained practically constant, varying less than ½ of one per cent during the rapid runs, and being absolutely constant during the slower runs.

[7] *Op. cit.*, p. 223.

The apparatus used to test the permeability of sands is shown in Figure 7. The apparatus consists of a series of chambers made of large threaded iron pipe in which the air was compressed by admitting water into the chambers. The apparatus is connected directly with the city water system, which has a pressure of 65 pounds, thus insuring an ample supply of water as rapidly as may be needed. The water is admitted into the apparatus through a 2-inch gate valve at *I*. It passes

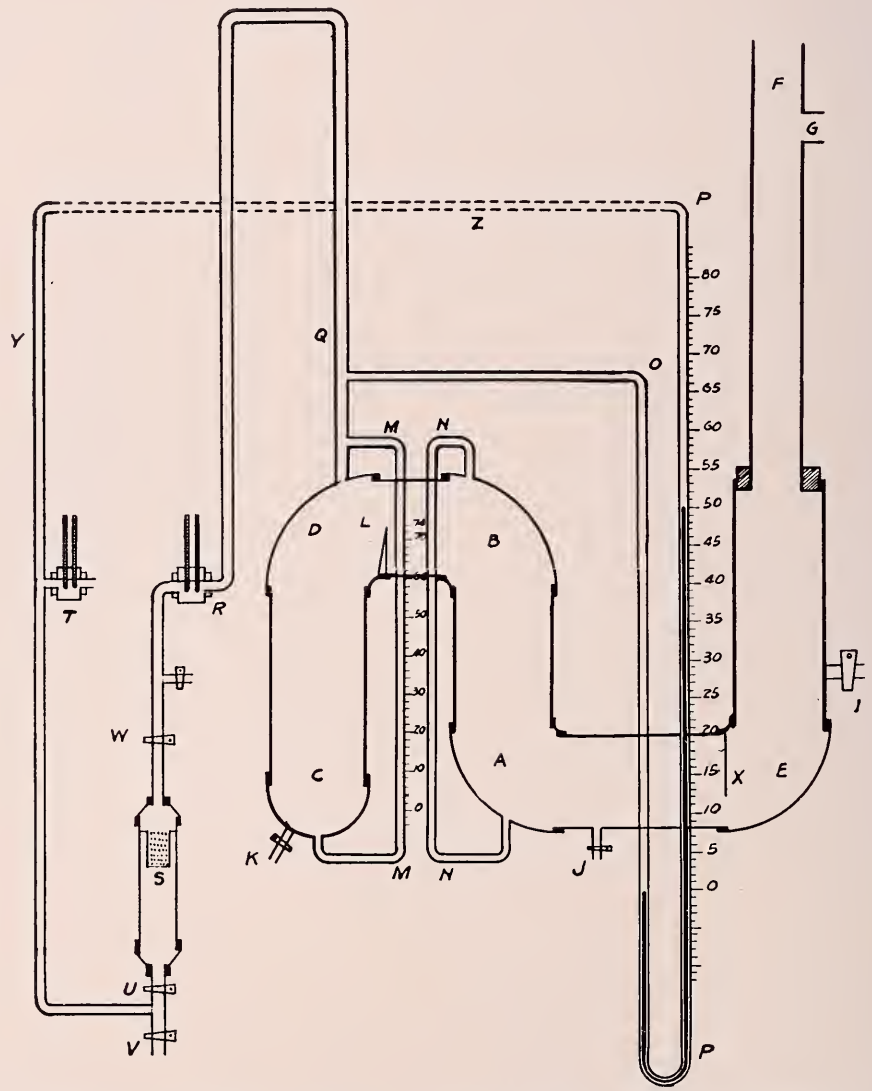

FIGURE 7. APPARATUS USED IN PERMEABILITY TESTS DELIVERING 74 LITERS OF AIR UNDER CONSTANT PRESSURE OF 50 INCHES OF WATER

through chambers *EA* and *AB* and into *CD*, each of which is 6 inches in diameter, compressing the air as it advances. A weir 6 inches across is provided at *L*, over which the water passes into chamber *CD*. A stand pipe 4 inches in diameter is provided at *F*, open at the top, with an overflow for waste at *G*. The waste gate *G* is 50 inches above the weir *L*,

which insures a uniform head of 50 inches of water, giving a pressure of about 4.5 pounds.

The compressed air is conducted through a 2-inch pipe *Q*, which extends 20 feet above the apparatus, returning to *R*, where wet and dry bulb thermometers are installed in the air line. From *R* the air is conducted downward through a common well cylinder in which the sand sample to be tested is mounted at *S*.

After passing through the sand *S* the air is carried upward and through a waste valve at *T* in which another set of wet and dry bulb thermometers is installed. A water manometer *OPP* is connected with the air line *Q* and provided with a scale, graduated to 1/10 of an inch. The manometer registers the pressure, 50 inches, direct, and variations in pressure can be read to 1/10 inch, or .2 of 1 per cent of the total pressure.

Chambers *AB* and *CD* are provided with glass water gauges *MM* and *NN*, which show the height of the water in these chambers at all times. The volume of chamber *CD* was determined by measuring water into it when the apparatus was installed. The glass gauge *MM* was provided with a scale, and the calibrations in half liters were marked on this scale as the water was measured into the chamber *CD*. The chamber *CD* holds 74 liters to the level of the weir *L*, which is the capacity of the apparatus. When in operation the amount of air that is passed through the sample is registered at all times by the position of the water level in gauge *MM*.

Waste valves are provided at *K* and *J* to empty the apparatus of water after a run is completed. A baffle at *X* serves to make the greater part of the air in chamber *AE* available for compression, and to prevent undue agitation in chamber *AE* when the city water under high pressure is admitted.

Control valves are provided at *U*, *V*, and *W*. The wet bulb thermometers at *T* and *R* have the bulbs wrapped with lamp wicking, and a small chamber filled with water is provided below the air line beneath the wet bulbs, in which the wicking is submerged, thus providing the wet bulbs with water to meet the needs of evaporation.

The upper end of the waste pipe *Y* is connected with the upper end of the manometer *P* to guard against, and register any back pressure that might result from friction or otherwise when air is passed rapidly.

The procedure in testing is as follows: The sand to be tested is mounted in the well cylinder at *S*; the valves *U* and *V* are closed; the valve *I* is opened, admitting the water into the apparatus rapidly so that it overflows in considerable volume at *G*. The rise of the water in chamber *AB* is registered in the glass gauge *NN*, and the rate the water rises here naturally declines as the pressure increases. The manometer

OPP records the pressure as it progresses. When the water in chamber *AB* reaches the level of the weir *L*, which is indicated by a calibration mark on the gauge *NN*, the manometer is read. The valve *U* is then opened allowing the compressed air to pass through the sample. When the water in chamber *CD* reaches the zero mark on gauge *MM* the stop watch is started and allowed to run until the water in chamber *CD*, as registered on the gauge *MM*, reaches the calibration 74, indicating that 74 liters of air have passed through the sand. The watch is stopped the instant the gauge *MM* registers 74, so that the time is recorded to a fraction of a second. The valve *I* is then closed, and the valves *J* and *K* opened to empty the apparatus.

The temperature of the room and the barometer is recorded at the beginning of each run, and the wet and dry bulb thermometers at *R* and at *T* are read three times or more during each run, viz., the beginning, at the middle, and at the end of the run.

The apparatus was readily tested against any possible leaks from defective mounting or improperly seated valves by allowing a little water to come over the weir into chamber *CD*, then closing the valve *U*, and allowing the water to run, wasting at the overflow *G*. If there were any air leaks the water would rise in the chamber *CD* and register on the gauge *MM*. Testing the apparatus consisted in allowing it to stand for a period equal to the time required to pass the 74 liters of air through the sample; that is, if it required 100 seconds to pass 74 liters of air through the sample, the apparatus was allowed to stand 100 seconds under full pressure. If the leaks were not appreciable in that time, they were neglected.

The pressure rarely varied more than .3 of an inch during a single run, which is .6 of 1 per cent. The variations in pressure were greatest with rapidly passing air; that is, when the time of passing the air was 50 seconds or less, the variation in pressure might be as high as .6 of 1 per cent, but when the time was 200 seconds or more, the variation in pressure was rarely more than .1 inch on the manometer, or .2 of 1 per cent. The average pressure for hundreds of tests was 50.45 inches.

The apparatus used for mounting the samples of sands is somewhat elaborate, due to the wide range of material tested. The main container consists of a common, brass lined, well cylinder 3½ inches in diameter and 12 inches long, the plunger and lower valve being removed, and the barrel of the cylinder with the upper and lower caps only retained. This is installed in the air line, as shown in Figure 7, between the valves *U* and *W*. A brass cup of heavy gauge metal (Fig. 6 *A*) was made to slip inside this cylinder barrel. It has a ¼-inch flange at the top, resting on the upper end of the cylinder barrel under the leather

gasket, insuring an air-tight joint. The bottom of the cup is heavy stiff brass, perforated. All of the samples were mounted in this cup, the method being adapted to the nature of the sample.

When damp or green sand is tested the sample is rammed into a special cylinder (Fig. 6 *B* and *C*) of the same dimensions used in the porosity tests, viz., 2 13/32 inches in diameter by 3 inches long, open at the ends and having a flange ¾ of an inch wide at the upper end. The flange rests on top of the cup beneath the leather gasket, thus insuring an air-tight joint, and compelling all of the air to pass through the sand core. The lower end of the sand core in this cylinder is supported by building up the bottom of the brass cup with discs of brass wire screen cloth of 20-mesh.

When loose sand was tested, the same cylinder (Fig. 6 *C*) was used. To retain the sand a false bottom of screen cloth was slipped on over the cylinder. The loose sand was compacted in the cylinder by rapping the side of the cylinder to jar the contents. The cylinders of loose sand were mounted in the brass cup in the same manner as the damp sand.

Where dry cores of sand (Fig. 6 *F*) were to be tested, it was necessary to provide some envelope that would fit the side walls of the core tightly enough to prevent any air by-passing along the sides of the core between the core and the envelope. Two types of envelopes were used to accomplish this purpose, and the cores were mounted in the brass cup as follows:

1. The cores by one method are coated with melted paraffin, care being exercised to have the paraffin no hotter than needed to apply it. If paraffin is too hot and fluid, it permeates the core and diminishes its permeability. After coating with paraffin, the core is set in the center of the brass cup, and the space between the core and the sides of the cup, about one half inch, is filled with puddled clay in a semifluid condition. The bottom of this space is filled with cotton waste and a little sand, to prevent the fluid clay passing through. This type of mounting was found to be absolutely impermeable.

2. The second type of envelope used for the dry cores consists of a sleeve of very thin sheet rubber, such as dentists use, which they call "rubber dam." These sleeves are made with a diameter less than the diameter of the core, vulcanizing the seam. The sleeves are stretched and slipped over the cores. The cores with rubber envelopes are mounted in the brass cup in the manner above described, using puddled clay in the intervening space. Paraffin was tried instead of puddled clay, but with unsatisfactory results, since the paraffin on cooling would shrink and draw away from the walls of the cup.

It is well known that to devise an apparatus that will deliver a definite volume of air at a constant pressure is a most difficult problem. The most serious fault with the apparatus used by King was that the volume of air employed was small and the pressure low, and because of this the barometric pressure with its diurnal variation, the humidity of the air, and the temperature of the air became important variable factors that had to be taken into account and determined with each run made. By greatly increasing both the volume of air passed and the pressure, these variables became practically negligible.

In making the tests of the permeability of the molding sands a record was kept systematically of the barometric pressure, temperature, and humidity of the air to determine to what extent these variables were factors in the problem; but it was found that the corrections necessitated on this account were so slight that they could be ignored without appreciably affecting the results.

RELATION OF POROSITY, TEXTURE, AND STRUCTURE TO PERMEABILITY

In ordinary sand and loam such as are used in foundries the interstitial spaces between the sand grains, called the voids, communicate with one another, forming continuous tube-like passages which the air in passing through the sand follows. They are very small, hair-like, in size. The movement of air through sand has been demonstrated by laboratory experiment to be comparable, within certain limits, to the movement of air through capillary tubes, indicating that the interstitial passages through sand are capillary in size.

The size of the interstitial tubes in sand is a function of the size and arrangement of the individual grains. Slichter has shown that in a mass of perfect spheres arranged in the most compact form, shown in Figure 8, the area of the cross section of an interstitial tube through the mass is $.1613\ r^2$, in which r is the radius of the individual sphere.[8]

The rate that air will pass through capillary tubes of different diameters and the same length is in proportion to the square of the area of the cross section of the respective tubes. With two capillary tubes the areas of the cross sections of which are 2 and 4 square microns respectively the rate of the passage of air through them would be in the ratio of 4 to 16. From which it will be seen that the size of the interstitial tubes in sand is of vital importance as effecting the permeability.

Texture in sand is that property which is related to, and dependent on, the size of the individual grains. For example, a sand in which the

[8] Slichter, C. S. Theoretical investigations of the movement of ground water: U.S. Geol. Survey Nineteenth Ann. Rept., part 2, p. 316, 1899.

grains were all of the 20-mesh size, or in which the 20-mesh sand predominated, would be said to have a coarse texture; whereas a sand in which all of the grains were of the 80- or 100-mesh size, or in which these sizes predominated, would be said to have a fine texture. Structure in sand has reference to the arrangement of the grains with respect to each other without regard to their size.

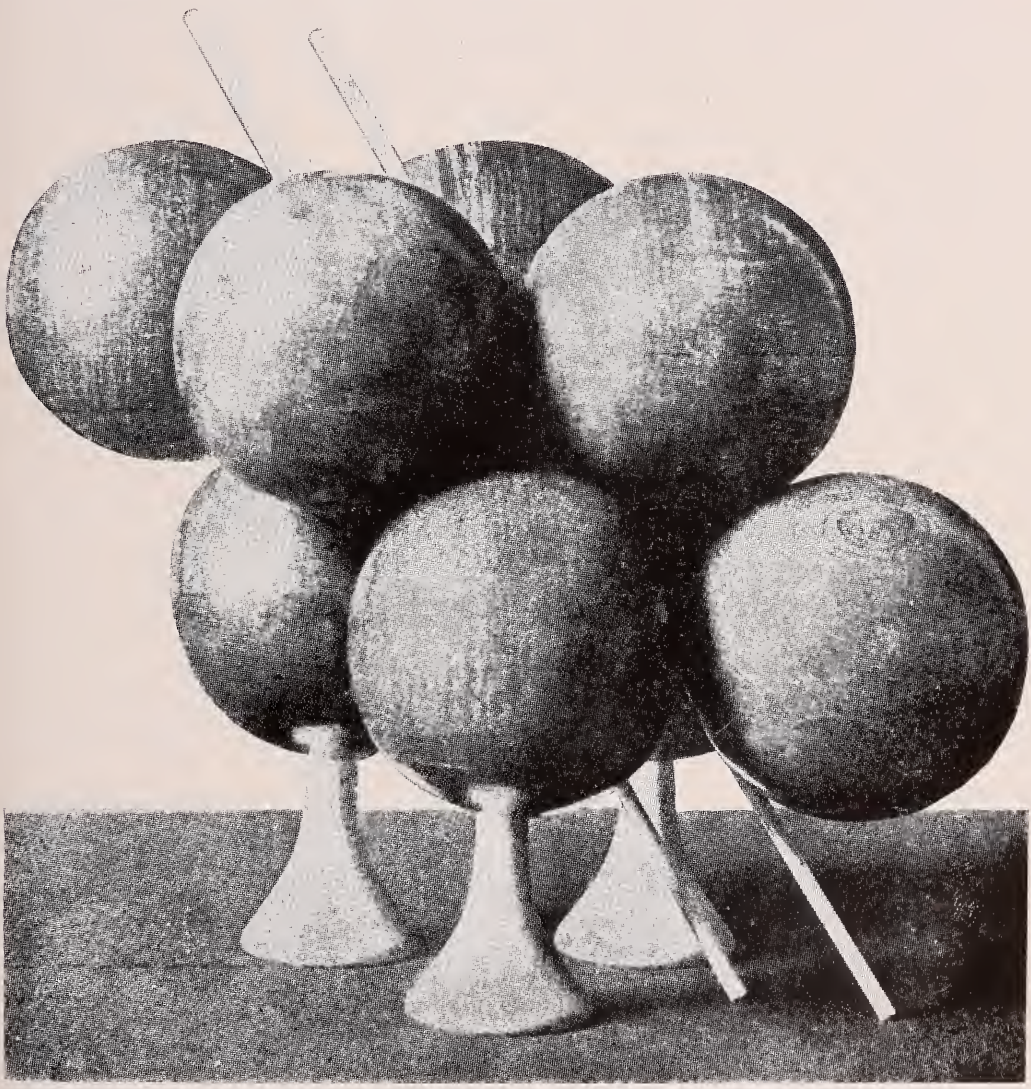

FIGURE 8. DIAGRAM SHOWING THE CLOSEST SYSTEM OF PACKING THAT IS POSSIBLE FOR SPHERES OF UNIFORM SIZE. THE RODS INDICATE LINES OF FLOW AFTER SLICHTER

The permeability of sand is dependent on each of these properties, the relative importance of which varies with the individual case. Reference to Figures 9, 10, and 11 may serve to make clear why this is true.

Figures 9A and 9B illustrate the effect of texture on permeability. The structure is the same in both 9A and 9B; that is, the spheres are systematically placed in the most open arrangement with each sphere

touching six other contiguous spheres. The spheres in Figure 9B, however, are just one half the diameter of the spheres in Figure 9A, and accordingly there are four times as many interstitial tubes in the mass 9B, as there are in the mass 9A. The total interstitial space, or porosity,

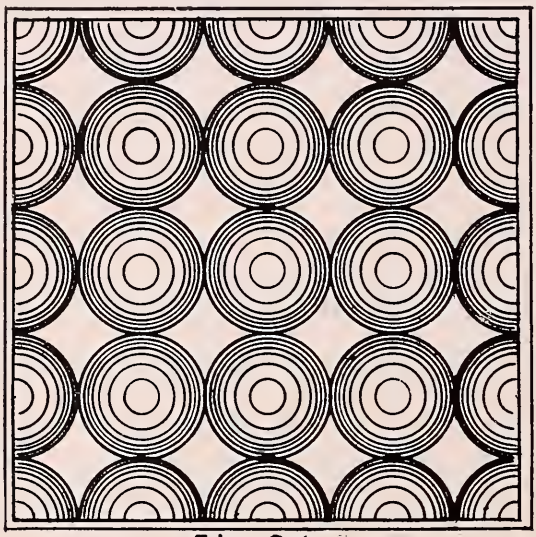

Fig. 9A

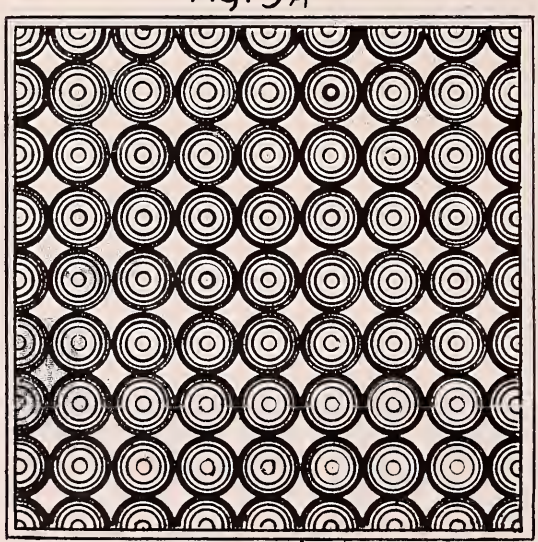

Fig. 9B

FIGURE 9A AND 9B. ILLUSTRATING STRUCTURE IN MASS OF SPHERES IN MOST OPEN ARRANGEMENT IN WHICH VOIDS EQUAL 47.6 PER CENT OF THE VOLUME OF THE MASS

After F. H. King

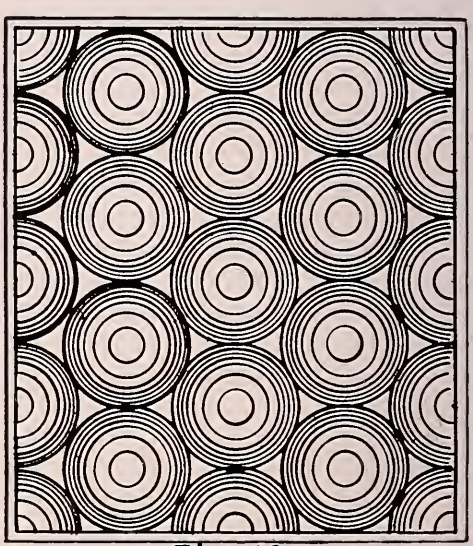

Fig. 10A

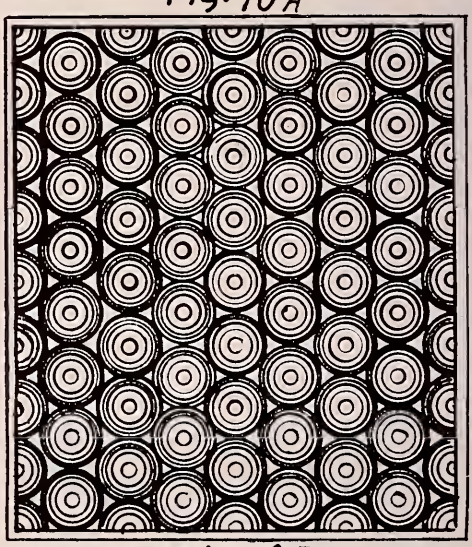

Fig. 10B

FIGURE 10A AND 10B. ILLUSTRATING STRUCTURE IN MASS OF SPHERES OF SAME SIZE AS FIGURE 9 IN MOST COMPACT ARRANGEMENT, IN WHICH THE VOIDS EQUAL 25.9 PER CENT OF THE VOLUME OF THE MASS

After F. H. King

is the same in both 9A and 9B, viz., 47.6 per cent. Therefore the interstitial tubes in the mass 9A must be four times as large as the interstitial tubes in the mass 9B. The areas of the cross section of individual tubes in the masses 9A and 9B would be in the ratio of 4 to 1; but according to the law stated in the preceding page the rates at which air would pass

through these individual tubes in masses 9A and 9B would be in the ratio of 16 to 1. Since there are four times as many tubes in 9B as in 9A the rate at which air would pass through the two masses 9A and 9B would be in the ratio of 4 to 1; that is, the mass 9A would be four times as permeable as the mass 9B, notwithstanding the porosity is the same and the structure is the same in the two masses. The only difference in the two masses is that 9B is of finer texture than the mass 9A.

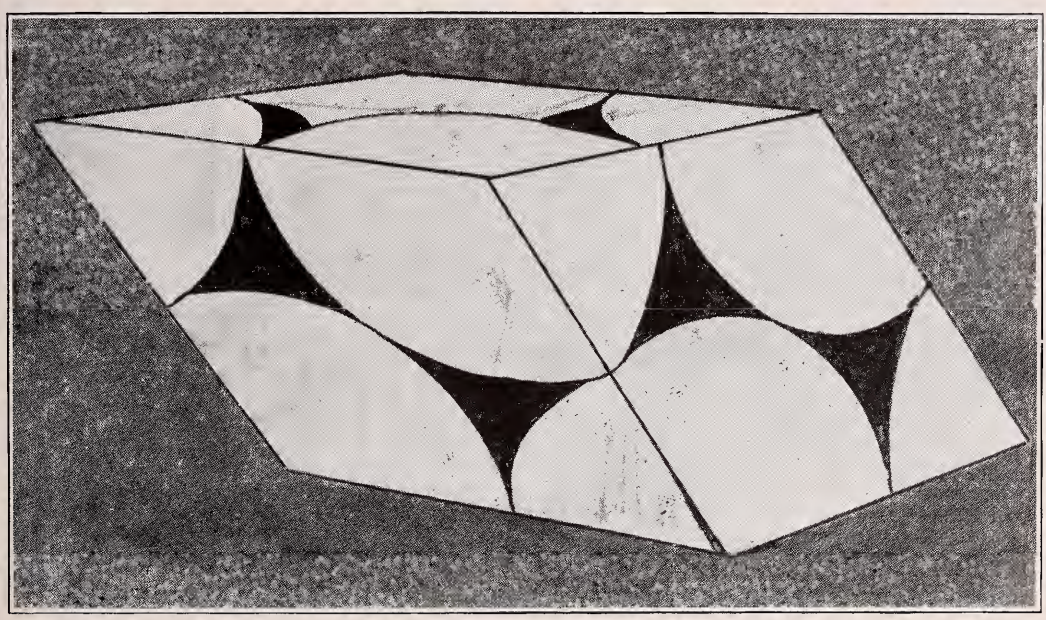

FIGURE 11. ILLUSTRATION OF RHOMBOHEDRON CUT FROM MASS OF SPHERES IN MOST COMPACT ARRANGEMENT, SHOWING ARRANGEMENT, RELATIVE SIZE, AND COMMUNICATION OF INTERSTITIAL SPACES
AFTER SLICHTER

The size of grain is the same in Figure 9A and in Figure 10A, but the arrangement of grains, or structures of the masses is different. The spheres shown in Figure 9A are placed in the most open arrangement possible, with each sphere touching six other spheres,[9] whereas the spheres shown in Figure 10A are in the most compact arrangement possible, with each sphere touching twelve other contiguous spheres. The porosity of the mass 9A is 47.6 per cent; that of 10A is 25.9 per cent. There are sixteen interstitial spaces in 9A and thirty-two in 10A, with an equal number of sand grains. The ratio of numbers of pores is therefore about 1 to 2.

If one pore in 9A had an area of 47.6 units, a single pore in 10A would have an area of about one half of 25.9 units, or 12.95 units, roughly one fourth the area of the pores in 9A. The permeability varying as the square of the area of a pore (here a tube) would be 16 times

[9] Four spheres only are shown in the figure which is a cross section but two other spheres are not shown; one is at the front, another at the back of section. In figure 10A only six spheres are shown of twelve that touch each sphere.

as great in each tube of 9A as for each tube of 10A. But there are about twice as many tubes in 10A, so that the permeability of a mass like 9A will be roughly 8 times as great as that of 10A. This great difference in permeability is independent of the size of sand grain used, so long as they are uniform spheres. The difference is wholly a matter of arrangement of grain or structure in the two masses.

Another illustration of the effect of structure on permeability is shown in Figure 12, where the intergranular spaces rather than the interstitial spaces determine the permeability of the mass.

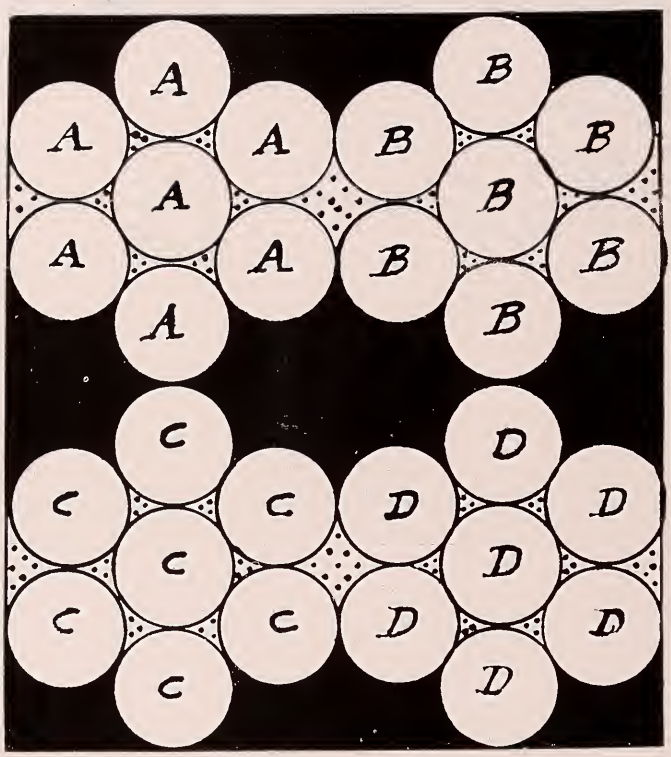

FIGURE 12. ILLUSTRATION OF GRANULATION IN WHICH SPHERICAL GRAINS ARE BOUND TOGETHER IN COMPACT GRAINS OR GRANULES ARRANGED IN OPEN STRUCTURE WITH LARGE INTERGRANULAR SPACES
AFTER LYON, FIPPEN, AND BUCKMAN

Each of four granules *A*, *B*, *C*, and *D*, is made up of spherical grains placed in the most compact arrangement, and the granules in turn are arranged in open structure so that each granule touches six other granules, leaving relatively large intergranular spaces. In a structure of this kind the spaces between granules or groups of spheres alone would amount to more than 40 per cent of the mass; in addition to which other spaces between spheres amounting to about 15 per cent of the entire mass, would give a total of about 55 per cent of voids. The smaller tubes between grains in the granules would be so small, however, compared

with the intergranular tubes, that they would have little effect on the permeability. Owing to the large intergranular tubes the permeability of the mass would be very great.

The case illustrated in Figure 12 is hypothetical. In natural sands the grains are never perfect spheres, nor are they ever symmetrically arranged. On the other hand in molding sand that has been tempered with the proper amount of moisture, granulation does occur and the permeability of such tempered sand is usually greatly increased as a result of the granulation. In soils these clusters or compound grains have been termed the "effective grain" because they behave as unit masses and give to the soil a structure and a permeability the same as though the soil were made up of particles of this size. In soils or in molding sand, however, the compound grains or granules may be made up of hundreds or even thousands of individual particles instead of a few particles as illustrated in Figure 12.

As to the effect of granulation on permeability in molding sands a single illustration will suffice. In Table XVI, it will be observed that with sand 240, in the loose dry state in which the sample had been pestled to break up the compound grains into individual particles, it required 2,027 seconds to pass a given volume of air through a standard cylinder of the dry sand, whereas the same sand moistened, tempered to facilitate granulation, and then rammed into the same cylinder allowed the same volume of air to pass in about one tenth of the time, viz., 244 seconds. The greater permeability of the same sand in the damp molded condition was plainly the result of granulation.

EFFECTIVE SIZE OF GRAIN

In natural sands of unassorted sizes the interstitial spaces between the sand grains vary greatly in size and are more or less haphazard in arrangement, but it has been demonstrated mathematically, and confirmed by laboratory experiment, that with clean loose sand grains of mixed size there is a mean, or average grain, called the "effective size"; and that the permeability of such sand is the same as though the mass were made up entirely of grains of this effective size. It has been shown also that within certain limits the movement of air through sands made up of grains of mixed sizes is amenable to the laws governing the movement of air through masses made up of grains spherical in form and symmetrical in arrangement.

It has been shown by Slichter that in masses made up of spherical grains in most compact arrangement the area of the cross section of interstitial tubes is $.1613\ r^2$, in which r is the radius of the individual sphere. But because of the irregularity in outline of the cross section of such a

tube, not all of this area is to be counted as effective in the passage of air. Making allowance for this factor, Slichter computes the effective area of cross section of interstitial tubes in granular masses such as above described to be .1475 r^2, in which r is the radius of the individual sphere in the mass.

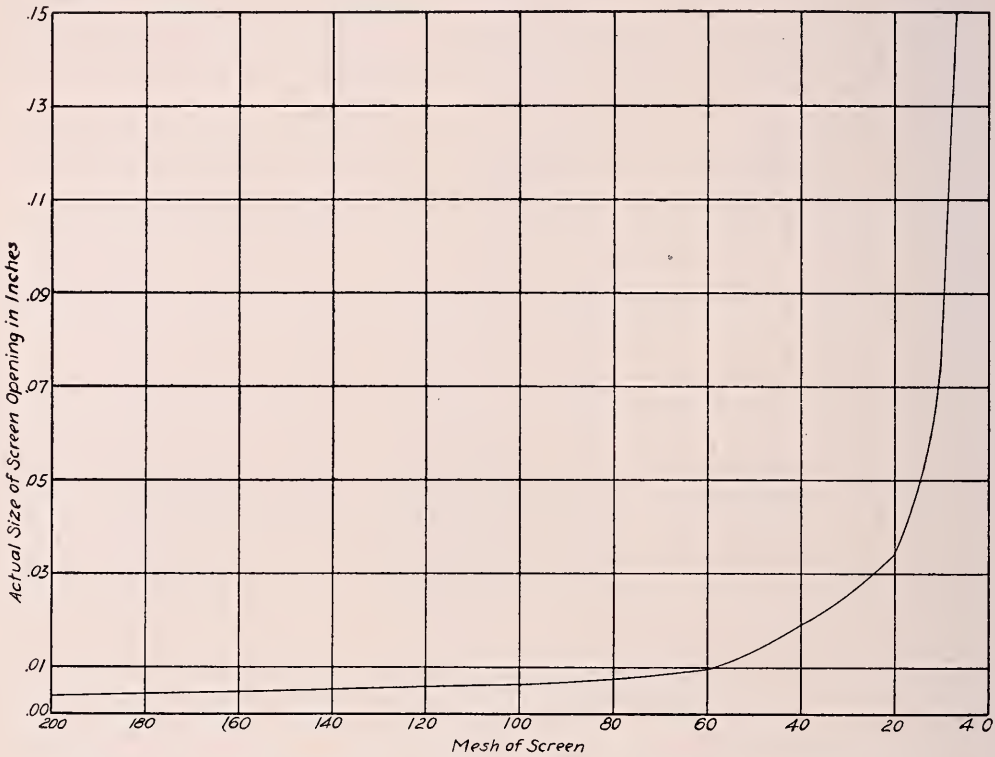

FIGURE 13. DIAGRAM SHOWING RELATIONS OF MESHES OF SCREENS AND ACTUAL SIZES OF OPENINGS

A determination of the size of the granules, or compound grains, was not attempted because numerous factors were involved, the relative values of which have not been determined. The laboratory work was devoted largely to special problems submitted by foundries, and a determination of the actual and comparative permeability as measured by the time required to pass a standard volume of air through particular samples of sand was all that was necessary.

METHOD OF COMPUTING PERCENTAGE PERMEABILITY

For comparing the permeability of sands, it is convenient to have some factor other than the time of passage of the air to express the relative permeability of different sands. Accordingly standard Ottawa sand was taken as a standard for comparison, and assumed to be 100 per cent permeable. The standard sand used in these experiments, sample 215, showed by screen analysis less than 1/10 of 1 per cent coarser than 20 mesh and less than 1 per cent finer than 30 mesh.

In the permeability apparatus sand 215 showed as a result of seven tests that it required 24 to 26 seconds to pass the standard volume of air, 74 liters, through this sand, giving an average of 25 seconds. Assuming this sand to be 100 per cent permeable and 25 seconds to be the time required to pass the standard volume of air through it, then the percentage permeability of the other sands was calculated by the formula $\frac{25}{Y} = Z$, in which Y is the time required to pass the standard volume of air, 74 liters, through the sand whose permeability is sought, and Z is the percentage permeability. For example, with sample 9, it required 94 seconds to pass the standard volume of air through the sand, accordingly $\frac{25}{94} = 26.6$ per cent, and 26.6 is taken as the per cent permeability of sand 9. Sample 240A required 2,027 seconds to pass the standard volume of air, and $\frac{25}{2027} = 1.2$ per cent is the permeability of this sand.

In making the permeability tests the same practice was followed as in making tests for bond, i.e., such samples as were molded were made in triplicate, and the average taken of three tests. A core box was used in most cases, permitting the making of three cores at a time. Where possible each core was run successively for green, for dry, and for baked test; that is, the core was put in the permeability apparatus directly from the mold and tested for permeability while damp or green. It was then allowed to stand in the laboratory 24 to 48 hours to dry, after which it was run again as an air-dried core. The same core was then placed in the bake oven at 400° C. for 4 to 8 hours, after which it was allowed to cool and was tested again for permeability as a baked core.

It frequently happened that the cores of sand molded directly in the solid cylinders became loose in the cylinders after drying, as a result of shrinkage from loss of moisture. In such cases the cores were removed from the cylinders and provided with a special mounting, using a seal of melted paraffin or puddly clay to insure against leakage of air around the sides of the core, and compelling all of the air to pass through the core itself.

The apparatus was so arranged that the pressure could be brought to the standard amount, namely, 50 inches water, and held there for any period desired. By observing the manometer and the water gauge, any leaks in the mounting were at once detected and corrected before making the run.

SHAPE AND ARRANGEMENT OF INTERSTITIAL TUBES IN SAND

The shape and arrangement of the interstitial spaces or voids in a mass of sand, and the manner in which these voids communicate to form interstitial passages or paths through the mass is illustrated in Figures 8 and 11. The grains of the mass in these illustrations are perfect spheres most compactly arranged, in which the pore space is about 26 per cent. It will be observed that the interstitial tubes through the mass, indicated by the rods, in Figure 8 are inclined at an angle of 30° from the vertical. They form passages following rectilinear paths through the mass, and as Slichter has shown the length of these passages or interstitial tubes is 1.065 times as great as a direct line through the mass normal to the base or top of a sand column. Accordingly in the cores of sand used in the permeability experiment, which were 3 inches long, the actual length of the interstitial tubes through these cores would be about 3.195 inches.

In the flow of air through capillary tubes the length of the tube as well as its diameter is a function of the rate of flow. The formula for computing the flow of air through capillary tubes was worked out experimentally by Poiseuille in 1842, and is known as Poiseuille's Law. The proper ratio of the length of a capillary tube to its diameter in order that Poiseuille's Law shall hold is about 6,000 to 1. This should be taken into consideration if the results given in Table XVI are to be checked against Poiseuille's Law.

Cores used in permeability tests of sands, loams, and clays.—The purpose of the permeability test was to obtain actual figures on the comparative permeability of different kinds of sand under conditions comparable to those in the foundries rather than as a study in permeability *per se*. The actual dimensions of the cores as finally chosen were determined by several considerations as follows:

1. The depth of the core, or length of the sand column, should be comparable to the thickness of the walls of molds in ordinary foundry work. Three inches was thought to be a fair average thickness for such molds, and accordingly a core 3 inches deep was chosen.

2. The structure in a sand mass adjacent to, or in contact with, the walls of the container is necessarily somewhat different from what it is in the center of the mass. This is especially true in damp sands that are rammed into the container, because of the drag of the sand on the side walls. Accordingly the larger the diameter of the container the less serious this factor becomes.

3. The air passages through a sand tend to follow rectangular paths and some of these paths meet the side walls and have their courses deflected. The larger the diameter of the container, the less the percentage of the air

passage that will be interrupted in this manner, and the more nearly the test cylinder approaches normal conditions.

4. A sand column the length and diameter of which are the same will probably most nearly approach foundry conditions, and accordingly a core was sought as near 3 inches in diameter as practicable.

5. It is desirable to use brass cylinders of heavy gauge so that the walls are not deformed, or the cross section of the sand column distorted by ramming sand into the cylinders, or by air pressure. Furthermore the plan of the work contemplated a large number of these cylinders for use in the foundries, and it was essential that they be as near the same dimensions as possible. It was found that common rolled brass tubing met the requirements, but such tubing 3 inches in diameter was not readily available and tubing 2 13/32 inches in diameter was chosen as the nearest approach to the dimensions desired. The containers were made by cutting sections 3 inches long from such tubing.

FUSION TESTS

The fusion tests of sands consisted in burning two or more briquets of the various sands in an electric furnace, the temperature of which was controlled, and noting the effect of temperatures ranging from 400 to 1,000 degrees C. The furnace was provided with a window or peep-hole, so that the behavior of the samples could be observed as the temperature was increased. Seger cones were used in the furnace along with the samples, following the usual practice in ceramic work, as a check on the furnace temperature. The laboratory work in fusion tests was not sufficiently complete to be made the basis of generalizations, but was suggestive in that some of the sands that had ample bond, and gave satisfactory results in the foundry, disintegrated into loose sand in the furnace at temperatures of 600 to 1,000 degrees C, whereas other sands burned into fairly hard brick at the same temperatures. In general the temperatures reached were not high enough to cause even incipient fusion, although in a few cases the stage of vitrification was reached.

MOISTURE CONTENT OF MOLDING SANDS

Certain tests for moisture content of molding sand were undertaken with the following objects in view: (a) to determine the moisture content in sands and loams in actual use in the foundries; (b) to determine whether or not better results in tensile strength or permeability might be obtained by increasing or decreasing the amount of moisture from that used in the foundries; (c) to determine the variation in the moisture in the molding sands in the same foundry from day to day.

The results obtained served to show that there was a considerable range in the moisture content in the same foundry from day to day in the same kind of molding, the variation amounting to 30 per cent in some instances. There was also a variation in different foundries using the same grade of sand, and doing the same class of founding.

There was a variation in the moisture content in the same foundry as between different molders using the same sand. The results are recorded in the tables on tensile strength and permeability and are discussed in that connection.

The method of taking samples for moisture determinations was to use two quart glass fruit jars with the ordinary rubber gasket to insure against loss of moisture. The samples were taken from the molders' tables or from the sand heaps in actual use.

The method of determining the moisture content consisted in drying 100-gram samples of the sand taken in the foundry in the sand bath at 100 degrees C. for 24 hours or longer until they ceased to lose weight, and counting the loss of weight as moisture.

MECHANICAL AND MINERAL ANALYSES OF CORE SANDS

Results of the mechanical analysis of core sands are recorded in Table IX. Forty samples were analysed, following both the dry method, A, and the wet method, B, above described. The analyses by the dry method, A, are not recorded except in cases where the wet method, B, was not completed. The 19 analyses recorded in Table IX were selected as being typical of the total number made.

Eight of the analyses given in Table IX are of samples obtained in the foundries of sands in actual use in core work. The remaining samples, the analyses of which appear in Table X, were collected in the field from various parts of the state as representing material similar in character to that in use for core work.

One sample, 252A, used for core work in exceptionally heavy gray iron work, was obtained by the foundry from local glacial drift, having been washed at the pit to remove the greater part of the clay, and screened to remove the gravel coarser than ¼ inch in diameter. The other samples of core sand in use in the foundries were obtained from the St. Peter formation in St. Paul and Minneapolis.

The analyses, Table IX, show that sand suitable for core work may be obtained from the St. Peter formation carrying less than one half of 1 per cent of clay, but most of the sands in actual use carry 1 to 2 per cent of clay.

The texture of the core sands in actual use in the foundries is indicated in a general way by the "mesh" recorded in Table IX. The range for samples of sand used, except 252, is from 52 to 72. Sample 5, with a comparative mesh of 52, is the common type. The method of computing the comparative mesh, and the purpose in using the term to express texture is explained above, under Laboratory Methods. Sample 90, showing a mesh of 38, was the coarsest sand found in the St. Peter formation.

For ordinary core work the St. Peter sand is very satisfactory, and there is an unlimited supply available. The strictly clean sand is not necessarily the best. Samples 28 and 31 were used in the same foundry, and both came from the St. Peter formation. Number 28 was a clean, white, quartz sand, whereas 31 was stained yellow by oxide of iron. The yellow sand was the more satisfactory, as it developed greater tensile strength and gave smoother surfaces to the castings.

Where coarser sand was desired for heavy core work, this was obtained by mixing sand from the Jordan formation, described under steel sand, with the St. Peter sand. Coarser sand is obtainable from the St. Peter formation, but it is usually present as comparatively thin horizons, of 2 to 6 feet, interbedded with sand of the finer type. It is not feasible in most instances to develop it because of the overburden of fine material, and because of the excessive expense of mining it by tunneling. It is cheaper ordinarily to purchase the coarser sand from the Jordan formation and raise the average mesh by doctoring the St. Peter sand.

Owing to the rather wide variation in the requirements of core sand for the different classes of founding, no single grade of sand meets all of the needs. For core work in brass, and light work in grey iron, a sand of about 57 average mesh is preferred, and for heavy work in grey iron and steel an average mesh of about 35. In general, while a clay content is not essential, 1 per cent of clay or even more, is no detriment. The entire absence of silts is preferred, but the presence of 1 to 5 per cent of silt does no apparent harm.

Samples 90, 145, and 278 were collected from the St. Peter formation at Cannon Falls, Rochester, and Northfield respectively and illustrate the uniformity of the sand in this formation throughout the state.

Sample 72 was collected at Daytons Bluff, St. Paul, from the St. Peter formation, and illustrates the type of very fine sand that occurs in the St. Peter formation at certain horizons.

Samples 152 and 279 were collected from pockets and lenses of sand that occur more or less commonly in the dolomitic limestone between the Jordan and the St. Peter formations.

Sample 104 was collected from the Cretaceous formation in Goodhue County. It is of no commercial importance.

The St. Peter and Cretaceous sands are largely quartz. Number 252 is a glacial sand and has about 22 per cent of minerals other than quartz. As it is being used successfully, it would indicate that mineral composition is of little importance. From the standpoint of refractoriness, those highest in quartz should be best, but actual practice shows that others can be used with a fair degree of success. In the northern part of Minnesota, glacial sands are used considerably for core work. One from Biwabik is used in the Virginia Foundry, and one from Brainerd is used by the Brainerd Foundry. Lake Superior sand is used for core work at Duluth to some extent.

TABLE IX. MECHANICAL ANALYSES OF CORE SANDS

Mesh of Screen	1B	5B	21B	28B	31B	64B	65A	67A
4— 10	.....	.....	.....	.....	.....	.....	.....	.....
10— 20	.....	1.40	.....	.....	.....	.....	.....	Trace
20— 40	.86	1.48	1.04	1.22	1.02	48.74	9.87	40.27
40— 60	16.24	56.66	41.38	54.68	40.58	39.56	58.76	40.45
60— 80	34.86	22.86	17.32	22.10	18.94	3.68	7.92	4.60
80—100	21.92	11.62	13.96	12.32	14.24	1.92	7.61	3.02
100—200	22.56	5.26	23.00	8.42	21.66	3.76	12.92	7.37
200-silt	1.04	.07	1.26	.24	1.36	.96	.26	2.42
15-minute silt	.10	Trace	Trace	.00	Trace	Trace	.....	.....
30-minute silt	.20	Trace	Trace	.00	1.00	.16	.....	.....
Clay	2.16	.05	1.44	.28	.46	.52	.....	.....
Total	99.94	99.40	99.40	99.26	99.26	99.30	97.34	98.13
Comparative mesh	72	52	59	55	59	39	51	41

1. Core sand, University of Minnesota, foundry, from St. Peter formation.

5. Core sand, Eagle Foundry, Minneapolis, used in grey iron work, from St. Peter formation.

21. Core sand, American Hoist & Derrick Foundry, St. Paul, used in grey iron work, from St. Peter formation.

28. Core sand, Northern Malleable Iron Works, St. Paul, from St. Peter formation.

31. Core sand, Northern Malleable Iron Works, St. Paul, from St. Peter formation.

64. St. Peter formation, Forty-second and Randolph Streets N.E., Minneapolis, four feet below top of formation.

65. St. Peter formation, same locality as No. 64, twenty feet below top of formation.

67. St. Peter formation, Washington Avenue N. and Thirty-ninth Street, Minneapolis.

TABLE IX—*Continued*

Mesh of Screen	72B	90B	104B	145B	152A	152B	252A	262A
4— 10	.....	.....	.....	.....	.....	Sand	2.28	.....
10— 20	.....	.....	.....	.....	.....	not	14.76	.....
20— 40	.16	57.00	3.12	48.92	20.36	screened	55.64	2.26
40— 60	.80	29.20	33.90	28.76	21.68	total	13.54	45.16
60— 80	.90	1.84	27.36	6.28	33.20	———	13.18	11.96
80—100	3.00	1.10	12.50	3.04	10.68	87.00	2.46	10.02
100—200	32.98	.94	12.02	5.40	6.65	.....	1.16	28.84
200-silt	59.52	.52	3.20	5.14	6.54	.....	.70	1.06
15-minute silt	Trace	.00	.60	Trace	.....	1.00	.....	.....
30-minute silt	Trace	2.48	.36	1.84	.....	5.00	.....	.....
Clay	1.76	2.26	5.62	3.40	.....	5.74	.....	.....
Total	99.12	95.34	98.68	102.78	99.11	98.74	103.72	99.30
Comparative mesh	230	38	60	41	52	.....	27	57

72. St. Peter formation, Daytons Bluff, St. Paul.
90. St. Peter formation, Cannon Falls, Minn.
104. Cretaceous formation, four miles southwest of Goodhue, Goodhue County, Minn.
145. St. Peter formation, Klines' quarry, Rochester, Minn.
152. Oneota formation, sand bed in limestone, Orinoco, Olmstead County, Minn.
252. Core sand, Eagle Foundry, Minneapolis, used in heavy core work from the glacial drift, washed.
262. Core sand, Soo Line Railroad Shops, used in brass founding, from St. Peter formation.

Mesh of Screen	278B	279B	282B	299A	299B
4— 10	.....	.....	.....	.....	.....
10— 20	.....	.....	.....	.....	Sand
20— 40	3.00	14.82	.42	.90	not
40— 60	22.00	57.62	29.20	48.94	screened
60— 80	26.52	16.30	16.54	19.44	total
80—100	18.00	5.00	13.84	14.04	———
100—200	21.28	4.54	31.58	15.50	98.54
200-silt	5.04	2.04	2.30	1.10	.....
15-minute silt	1.06	.16	.20	.....	.00
30-minute silt	1.22	.64	.20	.....	.18
Clay	1.40	1.82	2.26	.....	1.58
Total	99.52	102.94	96.54	99.92	100.30
Comparative mesh	68	49	68	57	.....

278. St. Peter formation, Northfield, Minn.
279. Shakopee formation, Cannon Falls, Minn., sand in limestone.
282. St. Peter formation, Twin City Brick Co., St. Paul.
299. Core sand, Flour City Ornamental Iron Works, foundry, Minneapolis, from St. Peter formation, used in brass and bronze ornamental founding.

MINERAL ANALYSES OF CORE SAND

NUMBER	64	104	278	252
Part examined (over 200 mesh)	97.66%	92.4%	90.8%	100%
Quartz	99.2	98.97	99.3	76.16
Tourmaline	.02	.01	.07	.01
Limonite	.01	.18	.....	.03
Kaolin	.....	.....	.26	.....
Dolomite	.....	.....	.....	9.41
Feldspar	.....	.....	.....	7.11
Igneous rock	.....	.....	.....	3.28
Hornblende	.....	.....	.....	1.41
Chlorite	.....	.....	.....	1.27
Augite	.....	.....	.....	.11
Magnetite	.....	.....	.....	.01
Biotite	.....	.....	.....	.01

MECHANICAL AND MINERAL ANALYSES OF STEEL SANDS

The results of analyses of the coarser quartz sands, known as steel, fire, and silica sand, are recorded in Table X. The chief difference between these steel sands and the core sands is in the size of the grains, that is the steel sands are coarser than the core sands as generally understood; but there are exceptions to this rule, for in very heavy work core sands are used quite as coarse as the so-called steel sands. Fire or silica sands are quartz sands of medium to coarse grain that are very refractory; that is, their ability to stand heat is equally as important as their texture. They may contain 2 per cent or more of clay, as does sand 9, but if so this clay also must be refractory.

Most of the silica sands, or steel sands used in the Minnesota foundries are obtained from the Jordan formation, and would probably show on chemical analysis 92 to 95 per cent silica. The St. Peter formation carries some coarse sand also, as shown above in Table IX, which is essentially the same as the Jordan sand; in fact the sized sands from the two formations can not be distinguished from one another. The quartz grains, particularly the larger ones, are exceptionally well rounded.

Samples 166, 167, 168, 170, 173, and 175, were collected from the Jordan formation in the valley of the Minnesota River between Mankato and Merriam Junction, while samples 8 and 19 were collected from the foundries, and came originally from this same region. The similarity in the analyses is apparent. There is a noticeable difference in the texture of the Jordan sands, the comparative mesh ranging from 28 to 42.

The wet analysis to determine the clay content was not made on all of the steel sands, but analyses 8 and 19, which are wet analyses, are representative.

Sample 136 was collected from the Jordan formation 10 miles north of the Iowa line, at Preston, Fillmore County, about 100 miles southeast

of the area in the Minnesota River Valley. It is of no commercial value, except locally, but is of interest as showing the nature of the Jordan sand in this part of the state. This sample was not particularly coarse, but was practically free of silt and clay.

Sample 151 was collected from the Jordan formation 35 miles north of the location just mentioned, at Orinoco, Olmstead County. It differs from 136 in being coarser and in carrying 2 per cent of clay and 3 per cent of silts. Samples 136 and 151 resemble the St. Peter sands.

Sample 160 was collected from the Jordan fomation in the valley of Zumbro River, 2 miles below Mazeppa, Wabasha County, 12 miles north of Orinoco. In coarseness and in the content of clay and silt it resembles the Jordan sands, 75 miles to the westward in Scott and Le Sueur counties, in the Minnesota River Valley.

Sample 9, from Massilon, Ohio, differed from the local sands chiefly in having a slight matrix of semi-refractory clay that formed a very uniform coating over the sand grains, which was sufficient to mold the sand.

Samples 185 and 186 were collected at Sandstone, Pine County, 80 miles north of St. Paul, from the Kettle River formation. The Kettle River sandstone is extensively quarried at this point for building stone and the rubble is crushed for concrete aggregate. The samples represent the sand screenings from the crushers, which has been used in foundries as steel sand with satisfactory results. This sand is rather finer than the Jordan sand, and carries more clay and silt.

Sample 188 was collected from the Sioux quartzite, Nicollet County, in the quarries near Courtland below New Ulm. The quartzite here along the quarry joints has disintegrated under the influence of organic acids and has reverted to sand. It is of no commercial importance, but is of interest as showing the character of the original sand from which the Sioux quartzite was formed.

Sample 200, Table XIV, while not listed as steel sand, might be used to advantage for that purpose. It consists of screenings from the crushers at Jasper, Rock County, Minnesota, where the Sioux quartzite is crushed for concrete aggregate. It is practically pure quartz, very refractory, nearly free from clay and silt, and extremely angular.

Steel sand is imported from Ottawa, Illinois, for use in the foundries of Minneapolis and St. Paul, and while no analysis of this sand appears in Table X, this Illinois sand was tested and found to be identical in physical composition with several samples of the Jordan sand of Minnesota.

In this connection attention should be called to a confusion of terms. Some founders understand the term Ottawa sand to mean sand from

Ottawa, Illinois, while others understand it to mean sand from Ottawa, Minnesota. That the two towns happen to have the same name is a coincidence only. The sands are essentially the same. The Ottawa, Illinois, sand, however, happens to come from the St. Peter formation, whereas the Ottawa, Minnesota, sand comes from the Jordan formation some 200 feet below the St. Peter formation.

The requirements for steel sand are somewhat varied and for this reason no one grade meets all needs. For some purposes a content of refractory clay sufficient to mold the sand is desired and if this can be obtained in the natural state it is preferred. The Kettle River sand comes near meeting these requirements; the sand from the Jordan formation rarely does.

Since it is desired that steel sands show a silica content of 97 per cent or over,[10] the analyses indicate that the Jordan, Kettle River, and Sioux are satisfactory from a mineral standpoint for such use.

The comparative mesh of steel sand is about 42. The absence of silts in steel sand is preferred, but 1 to 3 per cent of silt is not a serious detriment.

TABLE X. STEEL AND FIRE SANDS

Mesh of Screen	8B	9B	19B	136A	151A	151B	159B	160B
4— 10	.....	.....	.....	.....	.....	.....	.....	.....
10— 20	3.44	.74	4.02	.....	.36	Sand	3.08	1.18
20— 40	54.80	22.80	44.47	17.40	0.00	not	68.40	48.58
40— 60	29.54	26.06	27.08	28.88	20.02	screened	23.52	35.68
60— 80	4.68	25.08	5.56	31.96	36.40	total	2.52	9.04
80—100	2.30	10.00	3.96	15.52	13.72	———	.80	2.94
100—200	2.61	7.44	9.25	5.42	16.88	95.00	.42	.98
200-silt	.30	3.50	3.81	.28	12.44	.....	.02	.00
15-minute silt	Trace	.12	.63	.....	.....	1.00	.00	Trace
30-minute silt	Trace	1.40	.10	.....	.....	2.00	.00	.24
Clay	.25	2.00	.98	.....	.....	2.00	.46	.92
Total	97.92	99.14	99.86	99.46	99.82	100.00	99.22	99.56
Comparative mesh	35	50	40	51	71	.....	32	38

8. Steel sand, Gas Traction Foundry, Minneapolis, from Jordan formation, Ottawa, Minn.
9. Steel sand, Gas Traction Foundry, Minneapolis, from Massilon, Ohio.
19. Silica sand, American Hoist & Derrick Foundry, St. Paul, from Ottawa, Minn., Jordan formation.
136. Quartz sand, Jordan formation, at Preston, Fillmore County, Minn., 10 miles north of Iowa line.
151. Quartz sand, Jordan formation, at Orinoco, Olmstead County, Minn.
159. Quartz sand, Jordan formation, from Ottawa Sand Co., Ottawa, Minn.
160. Quartz sand, Jordan formation, at Mazeppa, Goodhue County.

[10] Ries, H., and Rosen, J. A., Report on foundry sands: Ann. Rept. of Geol. Survey of Mich., p. 42, 1907.

Mesh of Screen	166A	167A	168A	170A	173A	175A	185B	186B
4— 10	.....	.08	.....	.....	.....	.....	.....	.....
10— 20	.28	.00	2.24	1.76	5.34	3.64	.....	.....
20— 40	29.14	70.46	73.82	45.95	82.66	58.62	1.24	15.38
40— 60	62.20	26.00	22.18	35.36	10.48	30.80	39.56	21.08
60— 80	3.12	1.72	.56	7.08	.76	3.96	38.04	27.94
80—100	1.52	.58	.02	3.22	.16	1.44	8.84	15.44
100—200	1.66	.32	.20	3.98	.02	.48	5.84	9.60
200-silt	.12	.14	.16	.38	.....	.04	1.20	6.30
15-minute silt	.....	.....	.....	.....	.....	.....	1.90	.54
30-minute silt	.....	.....	.....	.....	.....	.....	2.10	1.98
Clay	.....	.....	.....	.....	.....	.....	1.06	1.12
Total	98.04	99.30	99.18	97.73	99.42	98.98	99.78	99.38
Comparative mesh	42	33	31	39	28	34	58	55

166. Quartz sand, Jordan formation, at Kasota, Le Sueur County, Holverson's pit.
167. Quartz sand, Jordan formation, at Kasota, at River Bridge.
168. Quartz sand, Jordan formation, 1½ miles west of Merriam Junction, Scott County.
170. Quartz sand, Jordan formation, at Ottawa, Le Sueur County, Hayes' pit.
173. Quartz sand, Jordan formation, at Ottawa, Le Sueur County, Rayners' pit.
175. Quartz sand, Jordan formation, at St. Peter, Nicollet County
185. Quartz sand, Kettle River formation, at Sandstone, Pine County.
186. Quartz sand, Kettle River formation, same locality as 185.

Mesh of Screen	188B	220B
4— 10	.....	.....
10— 20	1.38	.....
20— 40	39.08	46.62
40— 60	22.22	24.62
60— 80	19.76	14.24
80—100	7.48	7.30
100—200	5.26	5.92
200-silt	1.92	.74
15-minute silt	.34	.00
30-minute silt	1.88	.00
Clay	.32	.50
Total	99.64	99.94
Comparative mesh	44	42

188. Quartz sand, from Sioux quartzite, Nicollet County, near New Ulm.
220. Quartz sand, Jordan formation, at Ottawa, Minn., Potters' pit.

MINERAL ANALYSES OF STEEL SANDS

Number	8	136	185	188
Part examined (over 200 mesh)	97.37%	99.1%	93.5%	95.1%
Quartz	99.00	99.2	99.17	98.57
Limonite	.28	.03	.01	.81
Biotite	.01	.....	.....	.....
Tourmaline	.01	.01	.....	.....
Kaolin	.....	.....	.10	.....
Magnetite	.....	.....	.01	.....
Chlorite	.....	.....	.01	.....
Feldspar	.....	.....	.01	.01
Chromite	.....	.....	.01	.....
Hornblende	.....	.....	.01	.01

MECHANICAL AND MINERAL ANALYSES OF BRASS SANDS

The laboratory results of the mechanical analyses of brass sands are recorded in Table XI. About 75 samples of this type of material were examined, and 50 samples were subjected to analysis by both the dry method "A" and the wet method "B." The 34 analyses listed in Table XI are typical. The dry method analyses are omitted, except No. 70.

It will be observed from Table XI that the clay content of these sands ranges from 2.64 to 19.12 per cent. The 15-minute and 30-minute silts combined range from 4.00 to 36.47 per cent, and the comparative mesh ranges from 99 to over 250. The mesh is not stated for these sands but was calculated and nearly all ran above 150.

Of the 34 samples listed in Table XI, 18 were collected in the foundries and represents the type of material in actual use in molding in brass, bronze, aluminum, and the alloys of these metals. The remaining 16 samples were collected in the field in various parts of the state.

Four of the samples, i.e., 12, 213, 217, and 260, are floor sands; that is, sands that have been used one or more times, and consist of mixtures of raw brass sand and other materials, such as St. Peter sand and loam. The average mesh of these floor sands, which may be taken as representing the texture and constitution preferred in this class of work, ranges from 132 to 195, the clay content ranges from 3.46 to 5.80 per cent, and the silt content ranges from 4.94 to 11.28 per cent.

Four of the samples, i.e., 18, 210, 221, and 261, are so-called Albany sand, supposedly from Albany, New York. But the term Albany sand has come to be used as a trade name, and sands are sold under that name that do not come from Albany, New York. It is not known with certainty that any of the samples listed actually came from Albany. The founders only knew that the prices paid, including freight, were enough to have warranted the sands coming from that point.

NUMBER 75 Peter's pit, Fort Snelling. Furnishes brass sand	
Part examined (over 200-mesh)	74%
Quartz	95.82
Hornblende	1.12
Feldspar	1.08
Biotite	.85
Muscovite	.15
Augite	.12
Magnetite	.10
Iron oxide	.05

Comparing the so-called Albany sands, Table XI, it will be seen that the clay content ranged as follows, 7, 3.74, 4.30, and 10.56 per cent. The silt content in these Albany sands ranged from 5.64 to 11.76 per cent.

The two brass sands from Missouri, samples 10 and 29, show the same wide variation in both clay and silt content; that is the clay content

is 11.68 and 3.98 per cent respectively in the two sands, while the proportion of silt is in reverse order, viz., 7.66 and 21.6 per cent respectively.

The other brass sands exhibit the same wide range both in clay and silt content and in average mesh, from which it is apparent that the analyses afford no basis for a standard.

Sand 260, which was used for extremely heavy casting in brass, carried 3.96 per cent of clay and 4.94 per cent of silts, and may be close to the ideal brass sand. It is a mixture of so-called brass sand and other materials; it probably carries a considerable percentage of St. Peter sand.

Samples 16, 46, 48, and 51 represent material commonly present in the glacial drift in the vicinity of Minneapolis and St. Paul, occurring as irregular pockets and lenses. In view of the irregularity of the deposits and their lack of uniformity in quality, they are of little importance. Samples 75, 76, 77, 82, and 84 were collected in the Peters pit at Fort Snelling, which was the only pit furnishing brass sand to foundries at that time. These samples were collected in different parts of the pit and at different horizons from the surface to the floor of the pit, which was about 7 feet deep. The series shows the variation that may occur in the character of the material in this pit within a distance of a few rods. By selection of horizons in certain parts of this pit a very good quality of brass sand could be obtained, but uniformity in the grade is hardly to be expected. The analyses show that the clay content of the sands in this pit range from 2.87 to 13.64 per cent, and that the silts range from 4.08 to 31.23 per cent.

Samples 111, 124, 208, and 239 represent loess, vast quantities of which occur in the southeastern part of the state from Red Wing southward. The distribution is shown in a very general way in Figure 2. Thirty samples of loess were collected in various parts of the area and subjected to mechanical analysis. The four samples above mentioned, which appear in Table XI, are fairly representative of the group. The material is remarkably uniform in physical construction and is essentially the same as brass sand. In fact two tons of samples 208 were shipped to St. Paul and distributed among four different foundries and used as molding sand in brass with entirely satisfactory results.

Samples 295 and 296 were shipped in from Milwaukee, 295 being known under the trademark of "A.A.A." and 296 under the trade mark "A."

Because of the low temperature required for the melting of brass and its alloys, mineral composition would be expected to be less important than in other sands for foundry use. An attempt was made to make a mineral analysis of loess to contrast with that made on the

St. Peter, but the sand was too fine to give satisfactory results. The chemical analysis shows about what minerals are to be expected. See page 29. They undoubtedly include considerable feldspar, kaolin, and iron oxides.

XI. MECHANICAL ANALYSES OF BRASS SAND

Mesh of Screen	10B	11B	12B	16B	18B	29B	30B	32B
4— 10	.....	.....	.....	.....	.20	.....	.....	.....
10— 20	.....	.04	.....	.32	.30	.....	.....	.28
20— 40	.....	.16	.90	.44	.60	.12	.12	1.36
40— 60	.....	.25	1.40	2.08	.54	.00	.74	.92
60— 80	.01	.50	4.06	.74	2.32	.34	1.54	1.52
80—100	.02	1.42	4.84	.50	3.38	.12	11.32	.96
100—200	.04	18.31	22.98	2.10	22.82	.52	24.50	2.52
200-silt	80.10	64.74	53.06	66.22	53.48	72.20	49.10	60.58
15-minute silt	1.94	.57	2.66	10.48	1.90	11.82	2.44	6.86
30-minute silt	5.72	3.45	4.32	14.68	7.00	9.78	4.86	13.44
Clay	11.68	10.36	3.46	6.30	7.00	3.98	5.16	9.66
Total	99.51	99.80	97.68	103.86	99.54	98.88	99.78	98.10

10. Brass sand, Gas Traction Foundry, Minneapolis, from St. Louis, Mo.
11. Brass sand, Union Brass Works, St. Paul, from Monmouth, Ill.
12. Floor sand, brass, Union Brass Works, St. Paul.
16. Lens of sand in glacial drift, Lawson and Mackubin Streets, St. Paul.
18. Brass sand, American Hoist & Derrick Co., St. Paul, from Albany, N. Y.
29. Brass sand, Northern Malleable Iron Works, St. Paul, from St. Louis, Mo.
30. Brass sand, Northern Malleable Iron Works, St. Paul, from Fort Snelling
32. Brass sand, Herzog Foundry, St. Paul, local, glacial drift

Mesh of Screen	46B	48B	51B	70A	75B	76B	77B	82B
4— 10	.....	.....	.....	.....	.....	.....	.....	.....
10— 20	.08	.08	.....	.....	.....	.....	.....	.....
20— 40	.30	.44	.71	.54	.22	.21	.....	.....
40— 60	.40	.64	.29	1.84	1.71	1.03	.....	.....
60— 80	.30	.40	.21	4.36	5.72	1.38	.....	.04
80—100	.28	.46	.17	4.00	12.90	2.35	.12	.19
100—200	2.14	8.04	.46	20.28	43.83	18.66	2.27	6.02
200-silt	84.16	70.74	57.74	68.52	26.31	58.20	87.83	79.22
15-minute silt	2.00	3.00	19.31	.....	1.02	1.03	4.13	2.09
30-minute silt	2.00	6.00	17.16	.....	3.06	8.26	3.09	6.27
Clay	8.00	9.00	4.50	.....	5.15	8.77	2.87	5.96
Total	99.66	98.80	100.55	99.54	99.92	99.89	100.31	99.79

46. Pocket of sand in laminated clay, North Minneapolis, glacial.
48. Pocket of sand in glacial drift, Lyndale Ave. S. and Minnehaha Drive, Minneapolis.
51. Pocket of sand in drift, Forty-sixth Street S. and Minnehaha Drive, Minneapolis.
70. Brass sand shipped in to Minneapolis, source unknown.
75. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
76. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
77. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
82. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.

Mesh of Screen	84B	86B	111B	124B	208B	210B	211B	212B	213B
4— 10	.....	.40	.....	.....	.....	.....	.....	.....	.....
10— 20	2.04	.42	.....	.....	.....	.....	.....	.....	.72
20— 40	6.02	1.16	.06	1.10	.14	1.30	1.56	.60	1.98
40— 60	8.48	1.75	.04	3.16	.68	1.82	1.34	.52	1.74
60— 80	3.36	1.68	.18	5.94	4.74	2.54	3.00	1.64	3.48
80—100	2.80	1.43	.20	3.10	4.18	1.88	3.28	1.02	3.96
100—200	7.21	3.78	1.16	3.02	4.82	8.96	9.78	3.26	8.56
200-silt	24.77	56.65	59.86	64.74	72.50	67.04	60.68	62.64	59.92
15-minute silt...	7.54	6.52	4.56	2.30	3.84	4.68	5.96	7.36	4.10
30-minute silt...	23.69	17.16	12.00	6.00	5.22	7.08	9.00	15.02	7.18
Clay	13.64	9.04	19.12	9.00	2.64	3.74	5.90	6.14	5.80
Total	99.65	99.99	97.18	98.36	98.76	99.04	100.50	98.20	97.44

84. Fort Snelling sand pit, Peters, furnishing brass sand to foundries.
86. Loess, Pilot Knob, near Mendota, upland.
111. Loess, brass sand, 10 miles northwest of Red Wing, upland, 400 ft. above river.
124. Loess, brass sand, 1 mile northwest of Nerstrand, Rice County.
208. Loess, brass sand, Clay Bank station, Goodhue County.
210. Brass sand, from Albany, N. Y., University of Minnesota, foundry.
211. Brass sand, St. Paul Brass Founding Co., from "southern Minnesota."
212. Brass sand, St. Paul Brass Founding Co., obtained locally.
213. Floor sand, brass, Commutator Company, Minneapolis.

Mesh of Screen	214B	217B	221B	239B	260B	261B	295B	296B	297B
4— 10	.....	.....	.....	.....	.....	.....	.....	.....	.....
10— 20	.....	.....	.12	.....	2.22	.....	.....	.....	.....
20— 40	.14	1.32	.34	.10	2.84	.....	.....	1.42	.24
40— 60	.00	1.44	1.54	.12	2.44	.32	.14	12.70	4.24
60— 80	.24	5.56	.26	.18	1.22	.36	.24	17.46	4.84
80—100	.12	5.86	2.82	.20	2.22	1.00	.34	13.29	4.14
100—200	.22	18.26	38.42	1.54	21.60	16.34	4.14	30.79	38.48
200-silt	65.62	56.22	45.82	75.34	56.92	60.00	68.14	9.90	28.09
15-minute silt...	10.06	1.26	.88	5.48	.16	3.08	9.30	8.80	2.16
30-minute silt...	12.92	4.34	4.76	9.90	4.78	7.48	13.48	1.96	3.53
Clay	9.86	4.82	4.30	4.00	3.96	10.56	4.36	3.60	13.44
Total	99.18	99.08	99.26	96.86	98.36	99.14	100.14	99.92	99.16

214. Brass sand, Commutator Company, Minneapolis, source unknown.
217. Floor sand, brass, Twentieth Century Brass Company, Minneapolis.
221. Brass sand, Commutator Company, Minneapolis, Albany, N. Y.
239. Loess, brass sand, Farmington, Dakota County, Minn.
260. Floor sand, brass, Soo Line Railway Shops, Minneapolis.
261. Brass sand, Soo Line Railway Shops, Albany, N. Y.
295. Brass sand, from Milwaukee, Flour City Ornamental Iron Company, Minneapolis.
296. Brass sand, from Milwaukee, Flour City Ornamental Iron Company, Minneapolis.
297. "French sand," imported from France, Flour City Ornamental Iron Company, Minneapolis; facing sand, ornamental work.

MECHANICAL AND MINERAL ANALYSES OF LOAMS

The laboratory results of the mechanical analysis of foundry loams are recorded in Table XII. Forty-five samples of loam were collected and subjected to mechanical analysis, by both dry and wet methods. The thirty-four analyses recorded in Table XII are selected from the list

and are representative. The results by the wet method "B" only are given.

The thirty-four analyses recorded in Table XII include three types of material: (a) the raw unused loams taken from the stock bins of the foundries, which were used in making facing sands and floor sands, and for doctoring floor sands; (b) floor sands in actual use, which consist of mixtures of sands, loams, coal screenings (sea coal), etc., and which had been used one or more times; and (c) facing sands, which are mixtures similar in type to the floor sands, but more carefully prepared, and represent approximately, in so far as texture and clay content are concerned, the constitution sought in foundry loams.

The texture of the facing sands, floor sands, and loams is indicated in a general way by the "comparative mesh" in Table XII. For the facing sands the mesh ranges from 49 to 69, and the clay content ranges from 4.56 to 5.64 per cent. For the floor sands the mesh ranges from 46 to 90, with a clay content of 2.52 to 5.30 per cent. For the raw unused loams the mesh ranges from 33 to 250, with a clay content of 4.56 to 10.98 per cent.

Some of the floor sands were used without facing sand and others with facing sand, and in comparing them the grade of work should be taken into account. The most noticeable difference in the floor sands for heavy and for light work is seen in the mesh of the sand; the mesh of the sand for heavy work is 62 and 65, in sands 222 and 257, and the mesh for light work is 82 and 85 in sands 223 and 258.

In the 18 samples of fresh, or raw, loam collected in the foundries, the analyses of which are recorded in Table XII, the clay content ranged from 4.56 to 10.98 per cent. Some of these loams were used directly in molding without the addition of other materials, but most of them were used for "doctoring" the floor sands; that is, a little of the raw loam was added from time to time to the floor sand to replenish the clay as the bond was destroyed by repeated use; and for this purpose loam carrying an excess of clay is preferred since a less amount of new loam is required to bring the clay content to normal. The silts in these 18 samples ranged from 6.10 to 22.72 per cent.

All of the loams listed in Table XII were obtained in or near the cities of Minneapolis and St. Paul. Most of the loams were furnished the foundries by dealers in sands and loams. In Minneapolis practically all of the loam was obtained in the northeast part of the city, known as Columbia Heights, where the loam occurs as a mantle 2 to 6 feet deep, overlying the glacial drift, which forms a succession of small rounded knolls with intervening basins or kettle holes, that make the moraine of the last glacial period.

This loam is subject to wide variations in character within distances of a few rods laterally, and varies also from the surface downward, so that it is all but impossible to obtain a uniform product by the method of pitting it. A uniform product might be obtained by taking large batches and machine mixing the batch by the aid of a sand elevator and a series of riddles. In the absence of such mixing the loam requires close attention and repeated tests to know the actual constitution.

In St. Paul the loam occurs in the same relation, viz., mantling the glacial drift, and is obtained at numerous places, there being no well-defined or preferred area. In fact a considerable part of this loam is supplied by contractors making excavations for building foundations, who deliver to the foundries any material having the general appearance of loam that will pass inspection at the foundry.

In the vicinity of St. Paul and Minneapolis glacial drift of two periods is present. The upper or younger drift varies greatly in character from place to place, is essentially clayey in constitution, and rarely serviceable for foundry purposes. Beneath this young drift is an older deposit known as the Early Wisconsin, or red drift, which is less clayey and less variable in character. This red drift consists essentially of coarse sand with a moderate clay content, and in places very little gravel. A fair example of this material is shown in sample 254. Small amounts of this material were observed in a few foundries, having been provided by contractors as above noted. This material is worthy of a careful test by the foundries, since the clay it contains is more refractory than the clays in the surface loams, the body of the material is coarser, and in its natural state more nearly conforms to the requirements of molding loams.

Sample 163, Table XIV, was collected at Bellechester, Goodhue County, 20 miles by rail south of Red Wing. Extensive pits are operated here, mining a semi-refractory clay (Cretaceous) for the Red Wing potteries. Interbedded with this clay are thin beds of sand which are carefully separated from the clay and piled by means of cable and drag line in immense dumps. Sample 163 is a sample of one of the dumps representing hundreds of thousands of tons. This material is worthy of a careful test in the foundries because: (a) the clay in the sand is as refractory as any in the state; (b) the sand is nearly all quartz and well proportioned; (c) it is a waste, or by-product of the clay-mining and could be loaded on the cars at the same expense that it is piled in the dump, since the drag line runs over the gondolas for loading the clay; (d) the product would be more nearly uniform than the local loams now in use. It will be observed that by analysis 163, Table XIV, compares favorably with 22, Table XII, which is a synthetic sand and supposedly is correctly proportioned.

Synthetic sands and loams.—It might seem that synthetic sands offer the solution to the problem of foundry loams; that is, if carefully sized quartz sand were mixed with just the right proportion of good clay a loam could be made that would exactly meet the molding requirements. But when it is recalled that as soon as the loam is used in founding the clay is burned to some extent, and with each repeated use the clay bond still further deteriorates, it is apparent that no matter how carefully prepared originally, the sand rapidly changes in physical constitution with use. Not only is the clay destroyed as such, but the burned clay and burned sand become dead, silty material that does not function in the granulation, but serves instead to clog the interstitial spaces in the sand, interfering with the permeability. Synthetic sand therefore deteriorates with use, and sooner or later requires doctoring to replenish the bond, and to offset the silty material that gradually accumulates with use. A carefully proportioned synthetic sand rapidly approaches a constitution having the same objectionable features as natural loam.

The feasibility of synthetic sand resolves itself into a question of costs. If natural sands or loams, that approach somewhat closely the requirements, can be obtained it is usually cheaper to use these, bringing them to the standard by doctoring them at the beginning, rather than to build up the entire body by carefully proportioning several sands and clays. If natural sands or loams can be obtained the clay content of which is refractory, or semi-refractory, with the sand itself also refractory, the need for doctoring will be reduced to the minimum, and a long lived sand secured. In the light of present foundry practice this seems the more likely solution of the problem.

The clay content of each sample of loam is shown in Table XII. This is mechanically separated and not all of it is necessarily the mineral kaolinite, though much kaolinite is present. The minerals of the coarser portions were determined in five different loams. The quartz content of the portions examined ranges from 67 to 90 per cent. Feldspar is the most abundant mineral, next to quartz; and in the coarser sands, fragments of igneous rocks consisting of two or more minerals make up as much as 11.7 per cent of the sand. The figures for iron oxide include only grains of that material, and do not include coatings on grains. The amount varies from .27 to 1.61 per cent.

No extensive experiments were carried on to determine the effect of mineral composition on bonding power and refractoriness. The fact that all the sands except 254, which is a field sand, are being used successfully for some type of foundry work, indicates that aside from the clay content, the mineral composition within the limits shown is of minor importance.

TABLE XII. MECHANICAL ANALYSES OF LOAMS

Mesh of Screen	2	3	6	7	17	17x	22	23
4— 10	.....	.....	.....	.....	3.62	.....	.14	.48
10— 20	.82	.86	.54	.12	4.88	.70	.70	6.52
20— 40	6.98	5.74	5.82	5.44	16.32	2.08	5.70	15.28
40— 60	18.74	14.10	8.46	15.52	12.62	3.51	13.78	10.12
60— 80	7.40	6.08	12.90	22.00	14.70	1.73	24.12	11.22
80—100	6.10	4.22	6.66	5.30	8.44	1.64	20.00	6.92
100—200	15.46	10.98	10.48	9.30	12.06	7.67	15.00	9.18
200-silt	32.08	38.00	32.26	22.80	14.40	62.12	4.38	17.50
15-minute silt	2.32	2.00	4.92	3.34	1.16	4.39	.38	1.52
30-minute silt	4.44	6.00	6.88	5.52	4.94	9.87	5.14	6.76
Clay	5.02	10.80	9.96	9.32	6.18	6.24	11.42	10.12
Total	99.36	98.78	98.88	98.66	99.32	99.95	100.76	95.62
Comparative mesh	79	98	111	85	44	214	70	52

2. Floor sand, University of Minnesota, foundry, grey iron work.
3. Loam, raw, University of Minnesota, foundry, local, glacial.
6. Loam, raw, Eagle Foundry, Minneapolis, local, glacial, grey iron.
7. Loam, raw, Gas Traction Foundry, Minneapolis, local, glacial, grey iron.
17. Loam, raw, Valley Iron Works, St. Paul, grey iron, heavy work, local.
17x. Loam, raw, Valley Iron Works, St. Paul, grey iron, light work, local.
22. Synthetic sand; mixture of sands 19, 20, and 21, ratio 1:1:6.
23. Loam, raw, American Hoist & Derrick Co., St. Paul, grey iron, heavy work.

Mesh of Screen	24	27	33	222	223	224	225	226
4— 10	.....	.60	8.40	.10	.....	.06	.94	.24
10— 20	.12	1.00	5.56	2.02	1.20	.76	1.70	.92
20— 40	1.60	4.76	12.84	9.64	7.22	3.60	7.26	3.08
40— 60	1.42	3.40	9.66	12.56	8.96	1.98	6.76	2.14
60— 80	2.88	3.38	9.78	16.46	13.98	3.48	10.52	3.12
80—100	3.06	1.92	6.02	11.56	8.24	2.22	6.52	1.96
100—200	11.32	3.32	9.62	14.50	12.32	4.12	11.98	3.26
200-silt	59.12	48.28	17.80	22.14	35.54	50.14	31.44	51.48
15-minute silt	5.54	7.12	2.82	1.56	1.46	8.02	3.88	7.62
30-minute silt	8.40	15.60	9.02	4.60	5.10	14.16	8.86	14.60
Clay	5.52	10.98	8.38	4.00	2.88	10.80	10.00	8.98
Total	98.98	100.36	99.90	99.14	96.90	99.34	99.86	97.40
Comparative mesh	230	145	36	62	82	210	77	200

24. Loam, raw, American Hoist & Derrick Co., St. Paul, grey iron, light work.
27. Loam, raw, Northern Malleable Iron Works, St. Paul, light work.
33. Loam, raw, Herzog Foundry, St. Paul, grey iron.
222. Floor sand, Minneapolis Steel & Machinery Co., grey iron, heavy work.
223. Floor sand, Minneapolis Steel & Machinery Co., grey iron, light work.
224. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, local.
225. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, local.
226. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, local.

Mesh of Screen	227	240	241	242	254	255	256	257	258
4— 10	.....	1.52	.20	3.70	6.08	.....	.....	.....	.....
10— 20	7.06	1.34	.62	1.22	11.00	.24	1.58	1.30	.76
20— 40	20.72	2.98	2.00	2.54	20.52	2.48	6.70	9.54	6.96
40— 60	12.28	5.68	6.32	6.78	11.10	8.34	8.20	22.86	10.26
60— 80	14.16	13.20	22.90	14.72	12.94	4.74	9.40	9.52	16.32
80—100	6.34	14.74	16.66	14.36	6.40	3.98	7.20	5.92	6.22
100—200	9.20	27.52	24.88	25.86	9.78	9.30	8.98	11.42	18.76
200-silt	14.40	21.80	18.62	21.46	10.52	48.24	36.00	25.74	27.04
15-minute silt...	2.26	1.70	1.32	1.38	2.00	4.52	5.02	2.38	2.46
30-minute silt...	6.52	3.62	2.56	3.38	4.52	8.44	7.86	5.24	7.08
Clay	7.70	2.52	3.40	4.12	4.56	9.76	10.98	5.20	5.36
Total	100.64	96.62	99.48	99.52	99.42	100.04	101.92	99.12	101.22
Comparative mesh	49	68	90	55	33	183	57	65	85

227. Loam, raw, Minneapolis Steel & Machinery Co., grey iron, St. Paul.
240. Floor sand, Northern Malleable Iron Works, St. Paul. light.
241. Floor sand, Northern Malleable Iron Works, St. Paul. light.
242. Floor sand, Northern Malleable Iron Works, St. Paul. light.
254. Loam, raw, old red drift, 1349 Central Avenue, Minneapolis, field sample.
255. Loam, raw, Crown Iron Works, Minneapolis, grey iron work, local.
256. Loam, raw, Crown Iron Works, Minneapolis, grey iron work, local.
257. Floor sand, Crown Iron Works, Minneapolis, grey iron work, heavy.
258. Floor sand, Crown Iron Works, Minneapolis, grey iron work, light.

Mesh of Screen	259	266	267	268	269	270	271	272	273
4— 10	.....	.....	.....	.....	.....	.....	.....	.40	3.54
10— 20	.46	6.70	8.38	5.00	5.40	6.80	1.30	1.40	4.94
20— 40	10.32	21.60	21.04	14.34	17.10	22.30	2.40	3.88	13.84
40— 60	12.06	21.68	24.06	23.00	27.94	23.06	6.90	5.30	15.70
60— 80	21.58	6.06	5.82	6.34	6.60	5.98	3.47	2.40	5.64
80—100	12.78	4.06	4.70	5.08	5.20	4.06	2.68	2.56	4.08
100—200	12.24	9.36	10.48	11.88	11.34	8.96	10.04	9.10	9.88
200-silt	18.10	16.46	15.38	21.68	15.84	15.80	51.90	48.40	22.64
15-minute silt...	2.18	1.50	1.24	1.88	2.18	1.44	3.72	4.96	2.88
30-minute silt...	4.52	7.28	4.64	5.28	.00	5.98	9.92	8.64	7.28
Clay	4.56	5.92	4.26	5.30	4.76	5.64	8.84	8.72	8.86
Total	98.80	100.62	100.00	99.78	96.36	100.02	101.17	95.76	99.28
Comparative mesh	69	49	46	55	50	49	175	142	47

259. Facing sand, Crown Iron Works, Minneapolis, mixture, loam, sand, coal.
266. Facing sand, American Brake Shoe Co., Minneapolis, mixture, loam, sand, coal.
267. Floor sand, American Brake Shoe Co., Minneapolis, backing sand, grey iron.
268. Floor sand, American Brake Shoe Co., Minneapolis, light work, grey iron.
269. Facing sand, American Brake Shoe Co., Minneapolis, mixture, loam, sand, coal.
270. Facing sand, American Brake Shoe Co., Minneapolis, mixture, loam, sand, coal.
271. Loam, raw, American Brake Shoe Co., Minneapolis, grey iron work, local.
272. Loam, raw, American Brake Shoe Co., Minneapolis, light work, grey iron.
273. Loam, raw, American Brake Shoe Co., Minneapolis, heavy work, grey iron.

MINERAL ANALYSES OF LOAMS

Number	17	254	272	273	Kerrick
Part examined (over 200-mesh)	72.6%	77.82%	26.04%	80.2%	96%
Quartz	70.69	67.91	83.04	73.04	90.1
Feldspar	11.95	15.53	9.87	14.18	7.01
Igneous rock	11.71	11.11	1.43	6.30	.....
Hornblende	1.72	2.40	2.64	2.83	.46
Diopside	1.14	.56	.....	.....	.....
Iron oxide	1.02	.91	.27	1.61	.72
Chalcedony	.37	.....	.....	.....	.....
Augite	.27	.73	1.52	.66	.47
Tremolite	.13	.....	.....	.....	.....
Magnetite	.09	.06	.07	.17	.04
Biotite	.02	.....	.....	.....	.01
Tourmaline	.01	.01	.05	.01	.....
Zircon	.01	.....	.01	.01	.....
Bronzite	.01	.....	.....	.....	.....
Chlorite	.....	.72	.....	.43	.....
Serpentine	.....	.02	.....	.....	.....
Garnet	.....	.01	.....	.....	.....
Dolomite	.....	.....	.....	.54	.....
Slate	.....	.....	.....	.12	.....

CLAYS

Clay is a naturally occurring physical mixture of various products of rock-weathering in a very fine state of division, the individual particles of which range from about .005 millimeter in diameter to submicroscopic. The chief physical properties of clay are plasticity when wet; large absorptive power of water attended by swelling of the mass and the evolution of heat; absorption of gases and coloring matter; shrinkage on drying attended by absorption of heat; cohesive power in plastic state; and great tensile strength when dry. The constituents, as determined by chemical analysis, show a preponderance of kaolinite or some other hydrous silicates of alumina commonly considered essential.

In classifying clay according to its uses, Ries[11] cites 47 distinct uses made of clay in the industries and arts. The material used for these various purposes has come to be called clay, in common parlance, regardless of whether it is a pure mineral, or consists largely of impurities or inert material. In fact kaolinite rarely occurs in nature in the pure state; it nearly always occurs mixed with inert material or impurities such as sand and other rock fragments finer than sand, commonly called silts. Accordingly we have brick clays, potters' clay, china clays, modeling clays, etc.

Pure clay as such could not be used in most of the industries in which so-called clay is employed. Brick clays may carry less than 5 per cent of kaolinite, the remaining 95 per cent being inert material,

[11] Ries, H., Economic geology, p. 182, 1916.

principally sand and silt. Sample 59, Table XIII, shows by mechanical analysis only 1.5 per cent of the finest grained material, yet it is used for making brick.

The materials used in ceramic work under the name of clay commonly contain less than 50 per cent of kaolinite, but the other inert material present is just as essential as the true clay, so that it is not strange that the term clay is used to designate the heterogeneous mixture. By common consent any material that will develop a certain degree of plasticity is called clay in most of the industries using clay.

Colloidal material in clays.—It has long been known that certain substances in solution will diffuse through membranes whereas other substances will not, also that the same substance may be in such a state that it will diffuse through a membrane or it may be in such a state that it will not. Substances in the solutions that will not diffuse through a membrane are said to be in a colloidal state. Some substances exist under certain conditions in the colloidal and under other conditions in the non-colloidal state.

Colloidal materials may be organic or inorganic. The organic colloids include such common materials as jellies, albumen, gelatin, agar, and compounds of humic acid. The inorganic colloids include such common substances as silicic acid, ferric hydrate, and aluminum silicate. The colloidal state may be simply a matter of the fineness of division of the particles. It is thought that any substance can be brought into the colloidal state if it can be reduced to fine enough individual particles.

It is known that most, if not all, clays contain colloidal material, but the per cent of colloidal material in clay is small, rarely more than 3 per cent, and usually much less. The colloidal material in clay may be silica, alumina, ferric iron, or other inorganic material, or it may include organic material also.

It is thought by some investigators that the plasticity of clays is dependent on the colloidal material present in the clay, and that the absorptive power of clay for water and for coloring matter is also dependent on the presence of colloidal material. Moore, Fry, and Middleton[12] found that true clay, as well as clay soils, absorb coloring matter in direct proportion to the amount of colloidal material present.

Plasticity of clays.—Plasticity is that property in a material which enables it to change form without rupture, the new shape being retained when the deformitory force is removed. The cause of plasticity has not been satisfactorily explained. Some clays are much more plastic than others. Some clays that are of low plasticity develop greater plasticity under certain kinds of treatment, such as grinding, or weathering.

[12] Moore, C. J., Fry, W. H., and Middleton, H. E. Methods of determining colloidal matter in soils: Journal of Industrial and Engineering Chemistry, Vol. 13, 1921.

Clays that are richest in kaolinite are seldom as plastic as those that are not so pure. Plasticity does not appear to be connected with chemical composition, yet on heating to temperatures of 415° to 600° C. all clays lose their plasticity, and it can not be restored. It has been urged that plasticity is due to the shape of the clay particles, and there is some evidence in support of this claim, but the hypothesis remains unproved. Plasticity has been increased by bacterial inoculation, but it has not been proved that bacterial action is the cause of plasticity.

Whatever its nature and origin, it is fairly well established that many of the properties of clay are closely connected with the colloidal matter present, such matter being in the form of a film of colloidal gel surrounding particles of non-plastic inert nature.

Tensile strength of clays.—Tensile strength, or the resistance to torsional stresses, or to rupture in clays is influenced by the plasticity of the clay, the size and shape of the inert non-plastic grains in the mass, and the amount of colloidal material present.

In the mechanical analysis of molding sands, loams, and foundry clays, the material that would remain in suspension in distilled water 24 hours after deflocculation with ammoniated water, was called clay. No attempt was made to determine the amount of colloidal material present in this clay. The tensile strength developed in the molding sand, as shown by the briquet tests, varies with the proportion of clay present, but is not in direct ratio, that is, the same per cent of clay gives greater tensile strength in some sands than in others. In the same type of material, that is, material of the same origin, or from the same source, the tensile strength is approximately in proportion to the per cent of clay present.

The variation in the tensile strength may be due to the variation in the amount of colloidal material present in the different samples, or it may be due to differences in the sand, that is the proportioning of the fine and coarse sizes, the shape of the grains, etc. On the whole it seems more probable that the difference in tensile strength is due to differences in the clay itself in the different samples, which in turn suggests that the variation in the amount of colloidal material present in the different samples is the real cause of the difference in tensile strength. Much more detailed experiments would be required to obtain data on which a conclusion might be based.

Mechanical analysis of clays.—The results of the mechanical analysis of the so-called clays are recorded in Table XIII. Of the 17 analyses there recorded, 4 are analyses of clays collected in the foundries and 13 were samples collected in the field in different parts of the state, and used as clay for manufacturing purposes, or were material suitable for such use.

The clays collected in the foundries were used for various purposes, such as daubing cupolas, patching the lining of steel furnaces, doctoring burned out molding sand, and for making synthetic molding sand. The content of clay in the 17 samples as shown by Table XIII, ranges from 1.5 to 69 per cent. Comparing Table XIII with Tables IX, X, XI, XII, and XIV, it will be observed that many of the so-called sands and loams carry a larger per cent of "clay" than some of the samples listed in Table XIII, as clay. Even the St. Peter sand carries a larger per cent of "clay" than sample 59, Table XIII, which is a brick "clay."

The value of so-called clays for certain foundry purposes is roughly proportional to the per cent of clay present. Material that shows 20 per cent of clay is worth about twice as much as material that shows 10 per cent of clay, and the price paid for the material should be graduated accordingly.

Of the 17 clay samples listed in Table XIII, 8 came from the Cretaceous formation either directly or indirectly. They are numbers 10, 20, 129, 130, 132, 150, 164, and 171. They show a content of clay ranging from 28 to 69 per cent. Sample 265, supposed to be of more than ordinary refractoriness, showed a clay content of 37.02 per cent. This clay was imported from some other state, its original source was not learned.

Sample 164 was collected at Bellechester, Goodhue County, Minnesota, from the pits where clay was being mined for the Red Wing potteries. Several grades of clay are mined in this locality, but samples were not taken of all. Sample 164 does not fairly represent all the clays here found.

Sample 150, which had the highest proportion of clay, was collected a few miles north of Rochester, Olmstead County, Minnesota, from the glacial drift. A small mass of Cretaceous clay was here found in the drift, having been picked up by the glacier and incorporated without mixing with the foreign material. It is of no commercial value in itself, but is of interest in showing that deposits of exceptionally good clay occur in the region over which the glacier passed. It is within the range of possibilities that a systematic search might locate them.

Sample 130 was collected 2 miles east of Austin, Minnesota, 8 miles north of the Iowa line, from an outcrop of the Cretaceous.

Samples 45, 53, 58, and 59 were collected in North Minneapolis, in the Mississippi Valley above the falls, to illustrate the type of clays that occur here in considerable areas. It is improbable that this clay would be of much service in foundry work, since it carries a large percentage of lime, and other fluxes.

Clays similar in character occur at numerous points in the valley of the Minnesota River from Mankato northward to St. Paul, a distance

of 100 miles. The type is illustrated by sample 180, which was collected at Chaska, Scott County, where it is extensively used in the manufacture of common brick.

In a previous investigation of Minnesota clays,[13] samples were collected and analyzed from the same localities as those of interest in foundry work. They serve to indicate in a general way at least, the probable composition of the clays listed in Table XIII.

The clays used in the Red Wing potteries[14] came from Bellechester and Clay Bank, Goodhue County, and may be taken as probably similar to, if not the same as, 164 given in Table XIII. Three analyses of these clays show the sodium oxide, magnesia, lime, and iron oxides, amounting to 5.59 to 6.04 per cent. It is probable that samples 10, 20, 129, 130, 132, and 150 would show upon analysis about as much of these fluxing constituents. Similarly, a sample of clay from North Minneapolis shows 18.73 per cent of potash, soda, lime, magnesia, and iron oxides. This is from the same locality as samples 58 and 59, and is probably the same type of material. It is probable that samples 45, 55, and 180 would show upon analysis a similar composition. From these analyses it will be seen that the glacial clays carry more than three times as much of the alkalies, iron oxides, and magnesia as do the Cretaceous clays, and they are probably correspondingly less refractory.

TABLE XIII. MECHANICAL ANALYSES OF CLAYS

Mesh of Screen	10X	20	45	53	58	59	129
4— 10	.....	.....	.....	.....	.....	.....	.....
10— 20	.26	.90	.....	.....	.74	.....	1.32
20— 40	.44	2.00	.....	.....	.94	.....	2.52
40— 60	.32	3.60	.....	.....	.24	.....	1.94
60— 80	.50	2.22	1.04	.20	.24	.....	.70
80—100	.28	1.80	2.08	.18	.16	.14	.58
100—200	.80	3.46	.56	1.16	.62	4.52	1.34
200-silt	18.72	12.38	57.20	84.98	20.20	84.00	9.10
15-minute silt	1.62	2.76	10.40	3.24	5.00	2.00	2.58
30-minute silt	19.98	22.00	22.88	4.32	47.00	5.00	22.24
Clay	54.00	48.26	5.82	5.42	24.00	1.50	58.26
Total	96.92	99.38	99.98	99.50	99.14	97.16	100.58

10. Gas Traction Founding Co., Minneapolis, used in steel work, furnace, came from Ottawa, Minn. Cretaceous, furnace lining, and molding.

20. American Hoist & Derrick Co., St. Paul, came from Ottawa, Minn. Cretaceous, used in molding sand, and for furnace work.

45. River clay, North Minneapolis, City Work House, clay pit.

53. Glacial clay, Minnehaha Creek and Lyndale Avenue, Minneapolis

58. Marshall Avenue and Twenty-ninth Street N., Minneapolis, six feet below street.

59. Marshall Avenue and Thirty-fourth Street N., Minneapolis, brick yard.

129. Ottawa, Minn., sample furnished by Ottawa Sand Co.

[13] Grout, F. F. Bulletin, Minnesota Geological Survey, No. 11, 1914.

[14] Analyses by Grout. *Op. cit.*

TABLE XIII. MECHANICAL ANALYSES OF CLAYS—*Continued*

Mesh of Screen	130	132	150	164	171	180	253
4— 10	.18	.....	.....	.....	.....	.....	.48
10— 20	.18	.60	.....	.26	.....	.....	1.44
20— 40	.14	1.72	.....	.54	.24	.....	4.52
40— 60	.16	.86	.18	.14	.34	.....	8.24
60— 80	.28	1.16	.32	12	.18	.....	3.52
80—100	.37	1.70	.54	.50	.20	50.20	2.36
100—200	1.88	10.10	.90	7.72	.44	.....	6.16
200-silt	11.86	23.06	1.48	32.38	11.88	.....	36.22
15-minute silt	3.96	.98	7.70	4.60	4.12	11.28	6.28
30-minute silt	12.00	16.00	21.24	23.06	35.68	18.34	13.50
Clay	67.14	36.02	69.32	27.96	45.08	20.68	17.46
Total	98.15	92.20	101.68	97.28	98.16	100.50	100.18

130. Cretaceous outcrop, two miles east of Austin, Minn.

132. Cretaceous outcrop, bank of Iowa River, one mile above Le Roy.

150. Lens of clay in glacial drift, near Rochester, derived from Cretaceous.

164. Bellechester, Goodhue County, Minn., clay pit of Red Wing, potteries, Cretaceous.

171. Ottawa, Minn. clay pits, Cretaceous clay in pot holes in surface of Jordan formation.

180. Chaska, Carver County, Minn., Minnesota River Valley clay used for common brick, glacial.

253. Eagle Foundry, Minneapolis, local clay loam, glacial, used in daubing cupola, locality unknown.

Mesh of Screen	265	274	275
4— 10	1.03	.....	.....
10— 20	.62	.....	.48
20— 40	1.10	.50	2.60
40— 60	2.84	2.44	9.64
60— 80	1.44	2.20	5.44
80—100	1.44	1.84	4.40
100—200	4.84	7.10	12.48
200-silt	10.74	41.80	46.40
15-minute silt	5.64	4.38	3.46
30-minute silt	28.36	9.44	6.58
Clay	37.02	28.38	7.98
Total	95.07	98.08	99.46

265. American Brake Shoe Company, Minneapolis, imported clay, semi-refractory, used for furnace and molding.

274. Columbia Heights, Minneapolis, clay loam, furnished to foundries, extra heavy.

275. Columbia Heights, Minneapolis, ordinary loam, as furnished to foundries.

Samples 274 and 275 are included in Table XIII for purposes of comparison. These samples were collected in one of the pits at Columbia Heights, Minneapolis, which furnish loam to the foundries. Sample 274 is a fair average of the type of material here found. This sample is from a lenslike horizon of clay loam occurring in the main bed. It will be observed that 275 carries more clay than the glacial or river clays above described, i.e., 45, 53, and 59, and at the same time is not rated as clay—illustrating the confusion of terms.

TABLE XIV. MISCELLANEOUS SANDS

Mesh of Screen	4B	14B	25A	61	97	139	141	158
4— 10	.61	.....	26.00	.....	.....	.....	.....	.....
10— 20	.96	.68	29.50	.80	.....	.....	.....	.....
20— 40	7.78	4.36	31.00	10.06	.....	.....	.40	.96
40— 60	23.74	13.30	7.80	22.24	.....	.....	.56	1.10
60— 80	5.58	15.16	2.80	32.54	.....	.80	.82	4.22
80—100	6.02	14.36	1.00	14.44	.....	.36	.66	8.76
100—200	13.06	37.22	1.60	8.73	1.50	31.88	5.70	30.00
200-silt	28.94	9.90	1.10	3.20	75.20	51.70	50.00	46.00
15-minute silt	1.88	1.00	.....	.50	5.00	.18	12.00	Trace
30-minute silt	4.68	2.00	.....	2.00	8.00	4.00	14.00	4.00
Clay	4.96	3.00	.....	4.00	8.00	8.80	15.14	2.50
Total	98.21	100.98	100.80	98.51	97.70	97.72	99.28	97.54

4. Floor sand, Eagle Foundry, Minneapolis.
14. Wind blown glacial sand, East Hennepin Avenue, Minneapolis.
25. Blast sand, glacial, American Hoist & Derrick Co., St. Paul.
61. Dune sand, Fridley, Anoka County.
97. Dolomitic sand, 10 miles east of Cannon Falls.
139. Dolomitic sand, Fillmore County, 4 miles southwest, Wykoff.
141. Dolomitic sand, Spring Valley, Fillmore County.
158. Dresbach sand, Red Wing.

Mesh of Screen	161A	162A	163B	178B	181B	200B	205B	207B
4— 10	18.24	.96	.....	.....	.....	.....	.....	.....
10— 20	32.50	1.78	3.22	.....	.....	71.30	.30	.....
20— 40	27.20	20.12	30.62	.....	.....	25.28	8.80	.....
40— 60	9.84	43.92	18.48	.....	.....	.98	15.90	.....
60— 80	2.54	16.90	26.28	.10	.04	.58	25.92	.....
80—100	1.96	7.56	9.70	.08	.16	.08	16.36	.....
100—200	3.30	5.06	2.42	10.22	21.14	.10	16.66	.10
200-silt	3.86	1.96	.56	84.50	74.96	.16	9.76	61.62
15-minute silt	.....	.....	.24	1.50	2.24	.00	1.24	8.36
30-minute silt	.....	.....	.98	.62	.52	.48	2.98	24.70
Clay	.....	.....	8.76	.80	1.02	.62	1.56	3.88
Total	99.44	98.26	101.26	97.82	100.08	99.58	99.48	98.66

161. Cretaceous sand, Bellechester, Goodhue County.
162. Cretaceous sand, Bellechester, Goodhue County.
163. Mixed sands in dump, Bellechester, Goodhue County.
178. Silty River sand, Chaska, Carver County.
181. Silty River sand, Carver, Carver County.
200. Quartzite screenings, Jasper, Rock County, from crusher.
205. Quartzite screenings, Jasper, Rock County, from crusher.
207. Quartzite screenings, Jasper, Rock County, from crusher.

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MINERAL ANALYSIS OF MISCELLANEOUS SANDS

Number	61	158	163
Part examined (over 200-mesh)	99.66%	40.7%	97.5%
Quartz	89.05	98.841	96.54
Feldspar	9.51	.26	2.96
Limonite	.498	.003	.01
Hornblende	.489	.....	.009
Kaolin	.192	.....	.....
Chlorite	.072	.....	.....
Diopside	.042	.....	.....
Magnetite	.038	.016	.....
Rock	.008	.....	.....
Zircon	.005	.....	.....
Serpentine	.004	.....	.....
Tourmaline	.002	.....	.....
Spinel	.001	.....	.....
Garnet	.001	.....	.....
Mica	.....	.49	.....
Glauconite	.....	.006	.....

LABORATORY TESTS OF TENSILE STRENGTH

The laboratory work was guided to a large degree by the sand troubles encountered in the foundries visited, and was accordingly devoted to specific problems for the most part, rather than to systematic series.

Samples B 4, C 4, and D 4, all in Table XV, were collected in the same foundry, but from different sand piles. In this foundry the practice was to allow each molder to follow his own method of tempering the sand, and the purpose of the tests was to determine to what degree the personal equation of the molder was a factor in the tensile strength. The same raw sand was used by each molder. It will be observed that there was a variation of 50 per cent in the moisture content, of 15 per cent in the clay content, and a considerable variation in the tensile strength, in these three samples. The tensile strength in these three samples is not in proportion to the content of clay or of moisture. The maximum strength coincides with the minimum moisture and a medium clay content. Inasmuch as the same raw sand was used throughout the foundry, the variation in the clay content in the different piles is plainly due to doctoring the sands; that is, to the amount of raw sand added from time to time to replenish the bond as it is burned out, the amount so added varying with the individual molder.

Samples 240, 241, and 242 were collected in another foundry, but in the same manner as above described; that is, from separate heaps of sand in actual use for the same grade of work, and made by mixing the same original raw sands. In this instance, however, the sand for the entire foundry was tempered and riddled by one man whose business it was after closing hours, during the night, to prepare the sand for the following day. Even in this case, where exceptional care was exercised to obtain

uniformity in the sand, at least in so far as riddling and tempering the sand was concerned, there was still a considerable variation in the moisture, in the clay content, and in the tensile stength, indicating the need of some simple and easy method of making accurate determinations of these factors from day to day. The problem in this instance was not regarded as serious, but it was recognized by the foundry management that there was a lack of uniformity in the grade of castings turned out, which was attributed to the sand used, and that the difficulty might be corrected if its nature could be discovered.

Samples 222 to 227, inclusive, were collected from still another foundry where the sand trouble presented a problem of a more serious nature, because of the loss from defective castings. In this instance sands 224, 225, 226, and 227 represent the raw sands, or loams, furnished the foundry. Samples 222 and 223 were floor sands in actual use, taken from the separate sand heaps, and molders' tables, and were made by mixing the loams 224, 225, 226, and 227 in varying proportions.

The sand did not stand up in the mold, in consequence of which blisters and blow holes appeared in the castings. The mechanical analysis of sand 222 showed a clay content of 4 per cent which should have afforded ample bond. The moisture, however, was abnormally low, viz., 3 per cent. The tensile strength was so low as to be negligible. Adding water in the laboratory up to 10 per cent in this sample failed to develop the required strength. The tensile strength of the raw sands 224, 225, 226, and 227, as the table shows, was ample. This seemed to indicate a burned out sand, and a failure to add enough raw sand to counteract the burning from repeated use. However, the presence of 4 per cent of clay in sample 222, according to the analysis, Table XII, does not appear to be in harmony with this suggestion.

A second visit to this foundry showed that the work here consisted in making large, rather massive, castings in grey iron and semisteel. It was necessary for the castings to remain in the flask for a considerable time before being shaken out, and the sand of the entire mold became heated excessively. Without allowing the sand to cool down to normal, or to rest, water was added to replenish that lost from evaporation and the operation was repeated. Under this treatment the clay which should serve as the bond had no opportunity to function.

Time is an important factor in developing plasticity in clay, which appears to have been disregarded in this case. The trouble might be ascribed to what may be called a fatigue of the bond. The most obvious remedy was the use of a larger volume of sand so that the sand might have a rest between each period of use, allowing the water to be absorbed by the clay.

Samples 200, 201, 205, and 207 give the results of an experiment with crushed quartzite to determine the effect of extreme angularity of grain on tensile strength. From the mechanical analysis of these samples, Table XIV, it will be seen that 200 is coarse, 205 medium, and 207 fine sand. Number 200, which showed a clay content of .62 per cent, did not develop a measurable amount of tensile strength. It is of interest to compare this sand with sand 5 from the St. Peter formation, in which the clay content is even less, but the sand grains are well rounded, and in which a tensile strength of 2.8 pounds was developed in the air-dried briquet.

The individual grains of quartzite screenings represent the extreme of angularity, a large proportion of the grains being long, sharp needles or elongated prisms. The experiment, while not elaborate enough to carry much weight, points to extreme angularity of grain as a disadvantage rather than an advantage in tensile strength.

A second experiment was tried to determine to what degree the tensile strength test could be depended on to reflect the varying content of bond. For this purpose a series of mixtures of sand 1 and sand 208 were used, ranging from 90 per cent of the former, and 10 per cent of the latter, to 10 per cent of the former and 90 per cent of the latter. The results are recorded in Table XV, in samples 229 to 237 inclusive. The clay content and tensile strength of samples 1 and 208, the components of the mixtures, are shown elsewhere in the table. It will be observed that the clay content is comparable in the two, but that the tensile strength is twelve times as great in 208 as it is in 1.

From Table XV it will be observed that the tensile strength increases quite uniformly with the increase of the proportion of sand 208 (loess) until 80 per cent of this sand is reached, after which the change is not appreciable.

DETERIORATION OF SAND WITH HEAT

It is well recognized that the bonding power of sand deteriorates with repeated use, and unless the sand is doctored by adding new raw sand, or clay, or some artificial bond, it soon becomes so weak that it will not stand up in the mold. In this condition it is said to be burned out.

When the liquid metal is poured into the mold the sand on the face of the mold is heated to temperatures approaching the temperature of the melt, which in brass and its alloys is 800 to 900 degrees F. and in cast steel is about 3,600 degrees F. Back from the face of the mold the sand is heated to progressively lower temperatures. But while the sand in the body of the mold is heated to moderate temperatures only, it nevertheless deteriorates in strength. By way of demonstrating this the following experiment was undertaken.

Three samples of loess were taken from samples 208 and labeled 283, 284, and 285. They were placed in an oven at room temperature and the oven raised to a temperature of 400 degrees C., or 752 degrees F., which temperature was maintained. At the end of one hour sample 285 was removed. At the end of two hours sample 284 was removed, and sample 283 was allowed to remain four hours. After baking, the samples were subjected to the wet method mechanical analysis to determine the amount of clay that would stay in suspension in water. Briquets were made from the material after tempering with water, and the briquets tested for tensile strength with the results shown in Table XV.

The clay content of the original raw material, loess 208, as shown above, is 2.64 per cent, and the tensile strength is 18.2 ounces. The tensile strength decreased in proportion to the length of time the material was baked, the decrease amounting to nearly one third in sample 283 after four hours baking. The clay content decreased also, amounting to nearly 35 per cent in sample 283, baked four hours; and less amounts for the other samples baked shorter periods.

A second experiment of the same nature was undertaken using two surface loams from Columbia Heights, viz., 274 and 275, renumbering them 286 and 287. Both samples were baked four hours at a temperature of 400° C., after which the clay content was determined by the usual method, and the tensile strength determined by briquets. The mechanical analysis of samples 274 and 275 are shown in Table XIII, from which it will be seen that sample 274 before baking showed a clay content of 28.38 per cent, whereas after baking four hours, as sample 286, Table XV, it showed a clay content of only 5.84 per cent, or a loss of 79 per cent.[15]

Sample 275, as will be seen from Table XIII, showed a clay content of 7.98 per cent, whereas after baking four hours, as sample 287, Table XV, it showed a clay content of only 4.26 per cent, or a loss of 46 per cent.

The effect of baking these loams was probably partially to dehydrate the clays, in consequence of which they lost some of their plasticity and were less effective as bond. The clay also lost in part the property of deflocculating when churned in ammoniated water, and hence would not stay in suspension.

The results of these experiments indicate that the mechanical method of determining the clay by suspension in ammoniated water gives an approximate measure at least of the amount of clay present that is effective as bond, and that the tensile strength test by means of briquets is at least an approximate measure of the amount of such clay present in the sample.

[15] The term clay here used refers to the material that would stay in suspension in water 24 hours.

TABLE XV. TENSILE STRENGTH OF MOLDING SAND BRIQUETS

Laboratory Number of Sample	Moisture Content Per Cent by Weight	Clay Content Per Cent by Weight	Breaking Strength of Briquets			Nature of Sample and Conditions of Test
			Green	Air-Dried	Oven-Baked	
			In Ounces	In Pounds	In Pounds	
1	5	2.16	1.5	9		Core sand from St. Peter formation
B4	7	4.96	10.6	5.1	8.6	Floor sand from foundry
C4	10.5	5.12	7.8	10.8	42.9	Floor sand from same foundry as B4
D4	7.5	4.46	9.5	3.2		Floor sand from same foundry as B4
5	5	.05	1	2.8		Core sand from St. Peter formation
5A	5	1	3.4	5.0		Same sand as 5, clay added
5B	5	2.05	1.1	7.3		Same sand as 5, clay added
90	5	2.26	14.5	26.0		Sand from St. Peter formation, Cannon Falls
200	5	.62	0.0	1.0		Quartzite screenings, medium coarse
201	5	2.62	2.3	1.6		Quartzite screenings, 2 per cent clay added
205	5	3.56	2.0	1.86		Quartzite screenings, 2 per cent clay added
207	10	3.88	14.3	12.0		Quartzite screenings, very fine
208		2.64	18.2			Loess, from Clay Bank station, Goodhue County
222	3	4.0	.5	.2	.2	Floor sand in use, heavy founding
224	6	10.8	10.0	22.2	225.0	Loam, raw, used in foundry
225	6	10.0		15.0	17.7	Loam, raw, used in foundry
226	6	8.98		18.4	80.0	Loam, raw, used in foundry
227	6	7.7				
229	5	2.2 comp.	3.3			Mixture: 90 per cent sand 1, 10 per cent sand 208

TABLE XV. TENSILE STRENGTH OF MOLDING SAND BRIQUETS—*Continued*

Laboratory Number of Sample	Moisture Content Per Cent by Weight	Clay Content Per Cent by Weight	Breaking Strength of Briquets			Nature of Sample and Conditions of Test
			Green	Air-Dried	Oven-Baked	
			In Ounces	In Pounds	In Pounds	
230	5	2.24 comp.	5.0			Mixture: 80 per cent sand 1, 10 per cent sand 208
231	5	2.28 comp.	7.2		1.0	Mixture: 70 per cent sand 1, 30 per cent sand 208
232	5	2.33 comp.	8.1		1.5	Mixture: 60 per cent sand 1, 40 per cent sand 208
233	5	2.37	11.5		3.5	Mixture: 50 per cent sand 1, 50 per cent sand 208
234	5	2.43	14.9		3.0	Mixture: 40 per cent sand 1, 60 per cent sand 208
235	5	2.46	16.1			Mixture: 30 per cent sand 1, 70 per cent sand 208
236	5	2.52	17.6		16.9	Mixture: 20 per cent sand 1, 80 per cent sand 208
237	5	2.56	17.0			Mixture: 10 per cent sand 1, 90 per cent sand 208
240	7.7	2.52	8.7	7.2	14.7	Floor sand in use in foundry
241	7.0	3.40	6.1	12.7	17.0	Floor sand, same foundry as 240
242	8.1	4.12	8.8	8.9	13.5	Floor sand, same foundry as 240
257	12.0	5.20	10.3	13.3		Floor sand, in use in foundry, heavy work
258	9.2	5.36	17 00	22.00		Floor sand, in use for light work
259	8.5	2.56	10.77	17.2		Facing sand, mixture, grey iron work
260		3.96	9.25	2.2		Brass sand, used for heavy brass casting
266	8.4	3.92	8.5	7.7	2.0	Facing sand, mixture, grey iron work
267	7.5	4.26	7.5	1.5	Disintegrated in oven	Backing sand, in use in foundry, with 266

TABLE XV. TENSILE STRENGTH OF MOLDING SAND BRIQUETS—*Continued*

Laboratory Number of Sample	Moisture Content Per Cent by Weight	Clay Content Per Cent by Weight	Breaking Strength of Briquets			Nature of Sample and Conditions of Test
			Green	Air-Dried	Oven-Baked	
			In Ounces	In Pounds	In Pounds	
268	9.2	5.30	11.6	7.5	1.30	Floor sand, for light grey iron
269	9.4	4.76	5.7	4.0		Facing sand, for light grey iron
270	8.3	5.64	11.3	7.4	2.00	Facing sand, for grey iron work
283	10.0	1.72	12.8	3.7	1.6	Loess 208 after baking 4 hours
284	10.0	2.00	14.0			Loess 208 after baking 2 hours
285	10.0	2.20	16.0			Loess 208 after baking 1 hour
286	8.0	5.84	24.0	13.0	7.1	Loam 274 after baking 4 hours
287	8.0	4.26	24.0	12.0	7.4	Loam 275 after baking 4 hours
290	10.0	1.8	13.0	2.6	.60	Field sample
292		Molasses binder	24.3	16.3	0.0	Bronze sand, mixture 293 and 294
293		Molasses binder	21.0		0.0	Floor sand for bronze
296	8.0	3.6	5.0			Brass sand, from Milwaukee

TABLE XVI. PERMEABILITY TESTS

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
215 Standard sand	422	0	100	25	Standard sand, quartz, from Ottawa, Ill.; washed, dried, sized to 20 to 30 mesh
1 A	384	5	8.7	286	Core sand, molded, rammed hard, tested green
1 B	372	2*	14.4	173	Same cylinder as A, air-dried, tested dry
2 X	371	10	6.1	406	Floor sand, tempered, molded, rammed hard, tested green
2 Y	362.8	10	10.3	242	Floor sand, same as 2 X, rammed light, tested green
2 Z	363.1	10	8.9	280	Floor sand, same as 2 X, rammed medium, tested green
3 J	355	10	2.1	1,189	Loam, raw, tempered, molded, rammed hard, tested green
B 4 K	362	3.5	2.2	1,115	Floor sand as it came from foundry, rammed hard, tested green
C 4 K	355	2.0*	3.5	715	Floor sand, same as B 4 K tested after air dried
9 A	373	0	26.6	94	Fire sand, quartz, Massilon, Ohio, loose, dry, pestled
9 B		10	12.9	194	Fire sand, quartz, same as 9 A, molded, tested green
19	396	0	35.7	70	Quartz sand, raw, from Ottawa, Minn., dry, loose, pestled
21	410	5	7.6	327	Core sand, molded, tested green
200 A	311	0	78.1	32	Screenings, crushed quartzite, sized, 20 to 40 mesh, dry, loose
200 B	303	0	62.5	40	Screenings, crushed quartzite, sized, 40 to 60 mesh, dry, loose
200 C	315	0	73.5	34	Screenings, crushed quartzite, sized, 60 to 80 mesh, dry, loose
200 D	317	0	7.1	352	Screenings, crushed quartzite, sized, 80 to 100 mesh, dry, loose
208 A	356	0	1.3	1,944	Loess, from Goodhue County, Minn., loose, dry, pestled
208 B	363	10	13.9	180	Loess, same as A, molded, rammed hard, tested green
208 C	344	5*	10	250	Loess, same as B, air dried before testing
215	422	0	100	25	Standard sand, see head of list

* Indicates estimates or computations from incomplete data.

TABLE XVI PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
217 A	374		17.7	141	Brass sand, molded, furnished by foundry
217 B			3.7	664	Brass sand, molded, furnished by same foundry
217 C			2.9	860	Brass sand, molded, furnished by same foundry
218 A			31.2	80	Core sand, same foundry as 217, made in cores by foundry, resin for binder
218 B			44.6	56	Same sand as A, core made at same foundry, different mixture of binder
220	398	0	100	25	Quartz sand from steel foundry, dry, loose
221 A	406	13	6.5	384	Brass sand, from Albany, N. Y., tempered in foundry, rammed light, tested green
221 B		7*	7.0	358	Brass sand, same as 221 A, air dried before testing
221 C	394	10	3.2	765	Brass sand, same foundry as A and B, source of sand local, tested green
222 A		0	16.6	150	Floor sand, grey iron work, loose dry sand
222 B	400	6	3.0	831	Floor sand, same as A, molded, tested green
222 C	364	3*	6.5	384	Floor sand, same as B, but air dried before testing
223 A		0.6	14.5	172	Floor sand, same foundry as 222, loose, dry
223 B	396	10.0	3.5	714	Floor sand, same as A, molded, tested green
224 A	350	0	12.2	204	Loam, raw, same foundry as 222 and 223, loose, dry
224 B	334	10	3.8	648	Loam, raw, same as 224 A, molded, tested green
224 C	334	10	1.3	2,020	Loam, raw, same as 224 A and B, rammed extra hard, tested green
224 D	301	0	3.2	776	Loam, raw, same as 224 C, kiln dried before testing

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
223-224 A	300	10	5.1	492	Mixture, 90% of floor sand 223 and 10% of loam 224, molded, tested green
223-224 B		10	5.0	498	Mixture, 80% of floor sand 223 and 20% of loam 224, molded, tested green
223-224 C	397	10	6.2	399	Mixture, 70% of floor sand 223 and 30% of loam 224, molded tested green
223-224 D	382	10	7.1	353	Mixture, 60% of floor sand 223 and 40% of loam 224, molded, tested green
223-224 E	346	10	8.0	311	Mixture, 50% of floor sand 223 and 50% of loam 224, molded, tested dry
225	377	10	8.0	314	Loam, raw, used, same foundry as 222, 223, 224, molded, tested green
226	383	10	9.0	277	Loam, raw, used with 224 and 225, same foundry, molded, tested green
227	438	10	9.8	255	Loam, sandy, used with 224, 225, and 226, same foundry, molded, tested green
228 A	398	0	100.0	25	Quartz sand, sized to 20 to 30 mesh, loose, dry, from Jordan and St. Peter formations
228 B	395	0	73.5	34	Quartz sand, sized to 30 to 40 mesh, loose, dry, from Jordan and St. Peter formations
228 C	393	0	39.6	63	Quartz sand, sized to 40 to 60 mesh, loose, dry, from Jordan and St. Peter formations
228 D	384	0	23.1	108	Quartz sand, sized to 60 to 80 mesh, loose, dry, from Jordan and St. Peter formations
228 E	381	0	13.0	192	Quartz sand, sized to 80 to 100 mesh, loose, dry, from Jordan and St. Peter formations
228 F	375	0	7.8	320	Quartz sand, sized to 100 to 200 mesh, loose, dry, from Jordan and St. Peter formations
240 A	358	0	1.2	2,027	Floor sand, malleable iron work, loose, dry, pestled
240 B	351	8.7	6.5	383	Floor sand, same as 240 A, as taken in foundry, molded, tested green, rammed hard
240 C	338	8.7	7.0	356	Floor sand, same as 240 A, as taken in foundry, molded, tested green, rammed light
240 D	338	2*	10.2	244	Floor sand, same as 240 B, air dried

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
241 A	371	0	1.2	2,074	Floor sand, same foundry as 240, different pile, dry, loose, pestled
241 B	379	7	4.9	510	Floor sand, same as 241 A, molded, rammed hard, tested green
241 C		7	5.5	452	Floor sand, same as 241 A, molded, rammed light, tested green
241 D	344	2*	6.3	392	Floor sand, same as 241 A, molded, rammed hard, air dried before testing
242 A	353	0	1.2	2,051	Floor sand, same foundry as 240 and 241, different pile, loose, dry, pestled
242 B	373	8.1	3.4	734	Floor sand, same as 242 A, molded, rammed hard, tested green
242 C		8.1	7.2	346	Floor sand, same as 242 A, molded, rammed light, tested green
242 D		3*	4.0	624	Floor sand, same as 242 A, molded, rammed hard, air dried before testing
245 A	382	0	19.2	130	Core, made in foundry, using linseed oil as binder, baked in foundry, tested in laboratory, used with sands 240, 241, and 242. One part binder to 43 parts sand
246 B	352	0	28.1	89	Cores 246, 247, and 248 made in same foundry as 243, 244, and 245, using same sand, but resin as binder, in proportions of 1 of binder to 35 of sand
247 B	351	0	29.1	86	
248 B	358	0	26.6	94	
249 C	359	0	22	114	Cores 249 C, 250 C, and 251 C made in same foundry as 243 to 248 inclusive, using a mixed sand made of ½ floor sand and ½ raw core sand, quartz, using resin as binder in proportion of 1 part binder to 35 parts sand
250 C	361	0	21.4	117	
251 C	364	0	20.3	123	
257 A	347	0	1.6	1,550	Floor sand, grey iron foundry, heavy founding, loose, dry, pestled
257 B	360	10	8.7	285	Floor sand, same as A, molded, rammed hard, tested green
257 C	341	10*	13.6	183	Floor sand, same as A, molded, rammed light, tested green
257 D	347	3*	8.0	315	Floor sand, same as B, rammed hard, but air dried before testing
257 E	340	0	6.0	415	Floor sand, same as B, rammed hard, but baked at 400 degrees C. before testing

* Indicates estimates or computations from incomplete data.

TABLE XVI. PERMEABILITY TESTS—*Continued*

Laboratory Number of Sample	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
258 A	346	0	1.9	1,332	Floor sand, grey iron work, light founding, same foundry as 257, loose, dry, pestled
258 B	341	9.2	5.6	443	Floor sand, same as A, molded, rammed hard, tested green
258 C	332	9.2	7.8	321	Floor sand, same as A, molded, rammed light, tested green
258 D		3*	6.2	402	Floor sand, same as B, but air dried before testing
259 A	334	0	3.3	768	Facing sand, used with 257 and 258, mixture of 8 parts floor sand, 1 part quartz sand, 1 part loam 256, 1 part sea coal, tested loose, dry, pestled
259 B	357	8.5	4.3	575	Facing sand, same as A, molded, rammed hard, tested green
259 C	322	8.5	14.1	177	Facing sand, same as A, molded, rammed light, tested green
259 D	347	6*	5.5	454	Facing sand, same as B, but air dried before testing
260	380	10	2.8	878	Brass sand, railroad shops, casing heavy locomotive, brass journals, molded, tested green
292	368	8.06	1.8	1,395	Bronze sand, ornamental work, molded, tested green, made by mixing 1 part floor sand 293, 1 part "Red sand" 294, sample as used in foundry
293	392	8.06	2.8	880	Floor sand, same foundry as 292, used as backing sand for bronze work, and for ornamental iron casting, molded, tested green
296 A	418	Not determined	7.9	317	Brass sand, used same foundry as 292, bought in Milwaukee, molded, tested green
296 B	402	Not determined	11.4	218	Brass sand, same as A, but rammed light, tested green
297	303	Not determined	24.5	102	Bronze sand, imported from France, used for facing in bronze, molded, tested green

* Indicates estimates or computations from incomplete data.

Laboratory Number of Sample†	Weight of Test Cylinders of Sand in Grams	Moisture Content in Percentage by Weight	Permeability of Cylinder in Percentage of Standard Sand Permeability	Time, in Seconds, Required to Pass 74 Liters of Air through Test Cylinder	Nature of Sand and Conditions of Test
500	385	0	19.8	126	Cores 500 to 505 inclusive were made in the Eagle Foundry probably out of sand 5, and represent the type of core material used in grey iron work, in connection with loam 6. No information was obtained as to the kind of binder used or the proportion of binder to sand. Cores 500, 501, and 502 are probably of same sand. Number 503 may have been made of coarser sand than the others.
501	381	0	20.3	123	
502	381	0	20.2	124	
503	341	0	41.6	60	
504			20.3	123	
505	347	0	23.8	105	
506	361	0	16.9	148	Core 506 was made of 1 part of some commercial binder compound to 25 parts of sand (St. Peter) in Crown Iron Works. Cores 507 and 508 were made of the same sand and same binder as 506, but the ratio of binder to sand was 1 to 30.
507	353	0	21.7	115	
508	353	0	21.4	117	
509	382	0	14.9	168	Core 509 used linseed oil as a binder; the ratio of binder to sand being 1 to 45. Cores 510 and 511 were thought to be triplicates of 509, but legend was illegible. Made by the Crown Iron Works, and represent type of core material used in conjunction with loams 255, 256, and 259
510	382	0	15.8	158	
511	383	0	15.8	158	
512	364	0	25.5	98	Cores 512, 513, and 514 were made in the shops of the Soo Line Railroad, representing the type of core material used in brass-founding in conjunction with brass sand 261 (Albany sand). The St. Peter sand 262, was used in making the cores. The nature of the binder used was not stated.
513	360	0	25.5	97	
514	365	0	27.7	90	
515	387	0	20.6	121	Cores 515 to 523 inclusive were made in the foundry of the American Brake Shoe Co., Minneapolis. Cores 515, 516, and 517 are assumed to be triplicates as cores 518, 519, and 520, and cores 521, 522, and 523. They represent the type of core material used in conjunction with loams 271, 272, 273, and 266, 269, and 270. The sand used was presumably St. Peter, but the binder in each sample is not known.
516	381	0	25	100	
517	384	0	23.1	108	
518	381	0	21.9	114	
519	382	0	22.7	110	
520	383	0	21.2	118	
521	364	0	17.5	143	
522	370	0	16.0	156	
523	363	0	16.1	155	

† Samples 500 to 523 inclusive are cores made in different foundries in Minneapolis and St. Paul, in the standard core box furnished by the survey, with the core sand used in their regular foundry work, and such binders as they used in their foundry work, such as resin, linseed oil, flour, molasses, etc. Cores 515 to 523 inclusive were made using sand 277 and were made in the same foundry.

RESULTS OF PERMEABILITY TESTS

Permeability tests are recorded in Table XVI, and include tests of clean quartz sand of mixed sizes as obtained from the pits; the same quartz sand sized by the screen sieves to 20, 40, 60, 80, 100, and 200 mesh; loams in the dry state and in the molded state; brass sands, dry and molded; core sands, dry and with artificial bond; and various mixtures of sands, loams, and other materials employed in the foundries.

The permeability of the material is expressed in Table XVI in two ways (a) in the actual time in seconds required to pass 74 liters of air through the column of sand 2 13/32 inches in diameter and 3 inches long, at constant pressure (see page 43), and (b) in percentage permeability in which a standard sand is taken as 100 per cent permeable.

A few experimental tests were run on the permeability of carefully sized sands to test the apparatus and find whether the results agreed with those obtained by other workers with similar material, and to find to what extent the permeability test could be relied on as reflecting the structure in molding sands in general.

Permeability of sized sands.—Samples 228 A, B, C, D, E, and F were sized sands obtained by screening sand from the St. Peter and Jordan formations to the sizes shown in the table. The coarse sizes, A, B, and C, came principally from the Jordan formation, and the finer sizes, D, E, and F, came principally from the St. Peter formation. The nature of the material and the character of the grains were essentially the same in each case, that is, the sand was essentially pure quartz, the larger grains of which were exceptionally well rounded, and the smaller sizes less so.

It will be observed that the 20- to 30-mesh sand, 228 A, was 100 per cent permeable, agreeing with standard sand 215, and that the other samples, B, C, D, E, and F, showed a gradual decrease in the permeability consistent with the increase in fineness.

Samples 200 A, B, C, and D represent a second series of sized sands obtained by sizing quartzite screenings, resulting from crushing Sioux quartzite. The results of this tests were not entirely consistent, since the 20- to 40-mesh sand showed less permeability than the 40- to 60-mesh sand. Similar discordant results were observed by King,[16] in testing the permeability of crushed glass, sized to 20, 40, 60, and 80 mesh.

The series of samples 223-224, A, B, C, D, and E, represent an experiment with a series of mixtures of two loams, differing noticeably in permeability, to see in what degree the permeability of the different mixtures would reflect the proportion of the two loams present.

These loams were given 10 per cent of water after mixing and were rammed into molds in the usual way. They were tested green, except

[16] *Op. cit.*

in the case of E, which was tested loose dry. This series is of interest in that the mixture of 60 per cent of 223 and 40 per cent of 224 showed the maximum permeability of green sands, which was noticeably greater than the permeability of either of the constituents of the mixture.

Many samples were tested both as loose dry sand, pestled to break them up into individual grains, and also as damp molded sand. The molded sand was in some cases tested both as green, damp sand and as air-dried after molding. In general the molded sand, even when rammed harder than ordinarily, was more permeable than the loose dry sand. Most of these sands were loams in the proper sense of the term since they carried a considerable clay content, but they were sands in the sense foundries use that term. With some materials, however, different results were obtained, that is, the loose dry sand was more permeable than the damp molded sand, as for example in sample 9.

The difference in permeability of the sands in the loose dry condition and in the damp molded condition was plainly due to granulation. Some sands, when moistened with water, allowed to stand, and then riddled, granulated readily, developing clusters of grains of considerable size, and the granules were sufficiently coherent to stand up against ramming in the mold; so that after molding intergranular spaces remained large enough to make the mass more than ordinarily permeable. Other sands treated in the same manner did not granulate as in the case of sand 9; the subsequent molding served only to make them more compact than when dry, and the permeability was correspondingly less.

From the mechanical analyses, Table X, it will be observed that sand 9 is moderately coarse. The percentage of fines, including the silts, is small, and the clay content, 2 per cent, is sufficient for bonding purposes. Sands of that physical constitution do not develop granules that withstand ramming in the mold.

Examples of sands that granulated readily, gave conspicuously permeable masses when molded, and were rather dense, or but slightly permeable when dry, are seen in samples 208, 240, 241, 242, 257, and 259. Comparing the mechanical analyses of these sands, Table XI and XII, it will be seen that they show a rather wide range in constitution. If the fines alone are considered, it will be seen that the 30-minute and 15-minute silts and the sand passing the 200-mesh screen make 81, 27, 22, 26, 33, and 25 per cent respectively of the several samples. Sand 208, which shows an exceptionally large proportion of fines, is essentially a brass-molding sand, though not in general use, whereas the other samples referred to, ranging as low as 22 per cent of fines, are loams.

In Table XVI samples of 240 to 251, inclusive, come from the same foundry, and represent both the molding sands and the core sands used.

Samples 245 to 251, inclusive, were cores made in the foundry by skilled molders, using their own core sand, their own binders, and baking the cores in the foundry ovens, so that these cores were comparable in every way with their regular practice. The remarkable uniformity in the permeability of the cores made in triplicate illustrates the degree of skill attained by careful molders.

Samples 240, 241, and 242, representing the molding sand in this foundry, are ordinary loams, as will be seen from the mechanical analyses, Table XII. They carry 2.5 to 4 per cent of clay, and the usual percentage of fine and coarse sizes. The work in this foundry was in malleable iron, mostly small castings, where the soundness of casting and smooth surface finish were important.

This series of samples illustrates a close approach to the proper permeability for sands for light work in iron. It will be observed that the permeability in the green molds ranged from 3.4 to 6.4 per cent where hard rammed, and 4 to 10.2 per cent in air-dried molds. In Table XV it will be observed that this same series of sands, 240, 241, and 242, showed good tensile strength both in green and in dry briquets.

Samples 257, 258, and 259 represent another series of sands or loams in use for heavy work in grey iron. In this foundry a facing sand, 259, was used, and the molds were dried in all cases before casting. Number 259 D is the most significant test of this series and shows a permeability of 5 per cent. The sand used in this foundry back of the facing sand 259 was still more permeable and was used in the molds for heavy work. This sand, 259 D, as will be seen from Table XV, had a tensile strength, air-dried, of 17 pounds, and this was still further increased in actual foundry practice by spraying the inner surface of the mold, after completion, with molasses water and drying the surface by the aid of a torch. In this manner sand 259 was made to stand up, and give a good skin, or surface finish, to castings weighing several tons. Samples 506 to 511, inclusive, represent the type of core sand used in this foundry, in connection with the molding loams, 257, 258, and 259.

Sample 260 illustrates the permeability required for brass sand for heavy work, viz., 2.8 per cent. This sand was used in railroad shops for casting brass journals weighing 220 pounds for locomotives and gave exceptionally good results. Soundness of the casting was the essential feature in this work. It will be noted that the permeability is much less than for iron work. Samples 512, 513, and 514 are cores made from the core sand used in this railroad shop in connection with the brass sand, 261, the permeability of the cores being 25 to 27 per cent.

Sample 292, which was used for ornamental bronze work, shows only 1.8 per cent permeability, but the castings here were for the most

part light and a backing sand having a greater permeability was generally used.

Samples 500 to 505 were cores made in a foundry doing grey iron work, mostly light castings. No information was furnished by the foundry as to the nature of the bond used, the proportion of the bond to the sand, or whether the six samples were all the same or represented different mixtures. The results of the test indicate that sample 503 was a different mixture from the others.

Samples 506 to 511 represent a set of cores made by a foundry doing heavy founding in grey iron. Samples 507 and 508 were made, using a commercial binder with 1 part of binder to 30 parts of sand. Sample 509 used 1 part linseed oil to 45 parts of sand. Cores 510 and 511 were probably triplicates of 509.

Samples 515 to 523, inclusive, represent three series of triplicate cores, 515, 516, and 517 being one triplicate set; 518, 519, and 520 being a second set; and 521, 522, and 523 being the third set. No information was furnished by the foundry as to the kind of bond used, or the proportion of the bond to the sand, except that the cores represented their regular foundry practice. The foundry was working in grey iron, mostly light casting.

POROSITY TESTS

In setting up Table XVI figures on porosity were omitted, but upon further consideration it seemed advisable to give them, and they are shown in Table XVII.

The porosity percentages here given are of unequal value or accuracy by reason of the factors involved in some of the computations. With the samples of loose, dry sand the porosity was actually determined by the method described on page 41. For the neutral sands and loams the porosity percentages are dependable, but in the samples of floor sand or other used sand more or less foreign material was present such as chopped straw, sawdust, coal, etc., the specific gravity of which might be 1 or less than 1, or in any event less than the assumed specific gravity of 2.7. Again the used sands may or may not have contained particles of metal —brass, iron, etc., the specific gravity of which might be 5 or more; thus introducing into the computations factors, the value of which was unknown. Different cylinders were used for weighing materials for permeability and for porosity tests and the results of packing were not identical.

The porosity of the molded cores was determined by taking the actual weight of the core, which was of the same volume as the cup *V*, Fig. 6, and computing the porosity after the method described on page 41. For cores that contained only natural sand or loam, and were air-dried, the

TABLE XVII

Laboratory Number of Sample	Approximate Porosity in Percentage by Volume	Laboratory Number of Sample	Approximate Porosity in Percentage by Volume	Laboratory Number of Sample	Approximate Porosity in Percentage by Volume
215 standard sand	33.5	223-224 D	37.8*	258 C	50.8
		223-224 E	43.7*	258 D	
1	35.3	225	38.6	259 A	45.7
2 X	40	226	37	259 B	46.5
2 Y	39.4	227		259 C	50.9
2 Z	39*	228 A	35.4	259 D	46.5*
3 J	47*	228 B	35.7	260	43.7
B 4	42	228 C	36.2	292	44.0
C 4	42	228 D	37.5	293	41.1
9 A	37	228 E	38.0	297	
19	33.6	228 F	39.8	500	37.4
21	33.6*	240 A	41.8	501	38.0
200 A	49.4	240 B	46.3*	502	38.0
200 B	50.4	240 C	47	503	44.5
200 C	48.5	240 D	46	505	43.5
200 D	48	241 A	39.7	506	41.3
208 A	47	241 B	42.9	507	42.6
208 B	39	241 D	44	508	42.6
208 C	44	242 A	42.6	509	37.9
215	33.5	242 B	44.2*	510	37.9
220	35.4	245 A	37.8	511	37.7
221 A	34	246 B	42.4	512	40.8
221 C	35.9	247 B	42.6	513	41.1
222 B	34.9	248 B	43.4	514	40.6
222 C	39*	249 C	43.4	515	37.0
223 A		250 C	41.3	516	38.0
223 B	33.6	251 C	40.8	517	37.5
224 A	41.4	257 A	43.5	518	37.0
224 B		257 B	47.3	519	37.9
224 C	45.6*	257 C	49.5*	520	37.7
224 D		257 D	47.3*	521	40.8
223-224 A	42.2*	257 E	44.7	522	39.8
223-224 B		258 A	43.7	523	40.9
223-224 C	35.4*	258 B	49.4		

* Indicates estimates or computations from incomplete data.

porosity may be accepted as accurate, whereas for cores made of used sand the factor of variable specific gravity above mentioned may be involved and might affect the computation.

Again in computing the porosity of the damp, "green" molded cores the water content was deducted from the weight of the core on the assumption that the water was absorbed by the clay and did not affect the porosity, which assumption might be open to question.

It will be observed that the porosity of the standard sand used, viz., No. 215, is 33.5 per cent, and that practically all of the other samples run higher than that figure. The porosity of the air-dried cores also runs high, which is again consistent since they represent a structure in the mass abnormally open by reason of granulation. It is improbable that the variations in specific gravity above suggested appreciably affected the porosity computations, but this possibility must be taken into account.

As stated elsewhere, the percentage porosity is no measure, and not necessarily an index of the permeability; in fact, in a series of sands ranging from very coarse to very fine, and otherwise the same in constitution, the permeability would necessarily be in reverse ratio to the percentage porosity, which is illustrated by the fact that standard sand 33.5 per cent porous is 100 per cent permeable, whereas clay or heavy loam is 50 per cent or more porous, and practically impermeable.

CONCLUSIONS

From Table XVI it will be seen that there was a wide range in the permeability of the molding sands in actual practice. There is no very evident relation between the kind of founding done and the permeability of the mold. In foundries where the greatest care and most attention were given to the sand, the permeability of the mold ranged from 4.5 to 7 per cent, and these limits may be taken as normal for iron foundings. In brass founding the permeability of the mold may be taken as 1.5 to 3 per cent.

The permeability of cores may be taken as ranging from 15 to 30 per cent with little or no relation to the kind of work done, as evidenced from Table XVI. An exhaustive study of the problem would no doubt show a percentage permeability of the core varying with the nature of the founding done.

The material preferred for core work is a quartz sand with the least possible amount of silts, and with little or no clay, since organic bonds that will burn out in the founding process, leaving the sand loose or incoherent, are essential in most work. The St. Peter sandstone affords an abundance of this type of sand well suited to ordinary founding. Examples of this sand are samples 1, 5, 21, 28, 31, 64, 90, 145, 262, and 299, all in Table IX.

Coarser quartz sand, sometimes desired for cores in heavy work in grey iron and for founding in steel, may be readily obtained from the Jordan formation, examples of which are samples 8, 19, 159, 166, 167, 170, 173, and 175, Table X.

The permeability tests of the molding sands, some of which are given in Table XVI, brought out many interesting facts in connection with the permeability of the same materials under different treatments, and the relative permeability of different materials under like treatment. For example, with the same loam or sand dampened and molded, some loams showed greater permeability in the green or damp condition than in the air-dried condition, whereas with other loams the reverse was true. Again some sands or loamy sands showed greater permeability in the loose dry

state than in the damp molded state, whereas other sand showed the reverse. Such seemingly erratic behavior was evidently due to peculiarities in the physical constitution of the particular materials by virtue of which some readily took on a granular structure, whereas others did not, under the same treatment.

Tests of the cores made in different foundries indicated that the personal equation of the molder was an apparent factor in the permeability. Several cores made by the same molder, from the same sand at the same time under supposedly uniform conditions showed wide variations in the permeability of individual cores, whereas other groups of cores made by other molders in other foundries from similar materials showed remarkably uniform permeability. It is of course possible that some peculiarity in the foundry practice might account for these differences in part, and the personal equation of the molder may not have been wholly responsible. However, on the whole, the skill of the molder seemed in some instances to be the chief factor.

In sands where no artificial bond was used, and dependence was placed on the clay or other material inherent in the natural sand, variations were observed in the permeability which were not directly related to the percentage of clay present; indicating that the nature of the clay itself was a factor in permeability.

The percentage of silts in the sand affected the permeability of the sample differently in different types of sand, and also gave different results with the same sand in the various foundries. In the latter case the results would seem to be due to the foundry practice in handling the sand; but in the former, the difference in the behavior of the silts appeared to be due to some peculiarity inherent in the sand or the silts. Some sands, if properly handled, get rid of the silts by granulation, in which case the silts adhere to the larger grain, or the silts themselves gather into granules, giving an open permeable sand; whereas in other sands, no matter how handled, the silts remain as independent silty material that clogs the interstitial spaces, decreasing permeability.

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